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"There goes a MIGHTY

he just gave me an idea

Time Marches On

Ten years ago, the first issue of METALS AND ALLOYS was published. We said, in the first editorial, that the journal's task was "to collect, and to present impartially, information on the scientific advances in both ferrous and non-ferrous metallurgy in such form that they may be more readily assimilated into engineering practice, to bridge the gap between the sometimes abstruse findings of the research laboratory and the everyday use of those findings to make better and cheaper goods for human consumption."

No one then anticipated how tough the intervening years would be for industry, especially for the metallurgical industries. Ups and downs were expected, but harassment and hostility to those occupied in making better and cheaper goods were not. Mankind as a whole then seemed to be made up of friendly gentlemen with a policy of live and let live. Self-seeking politicians were not attempting starry-eyed reforms or creating emergencies in the hope of perpetuating themselves in office. Rubber-stamp Congresses, punitive legislation and taxation, vicious moves like the attempt to pack the Supreme Court, sit-down strikes fostered by state and federal administrations, and the other forms of one-man misrule were not in evidence. Executives were not forced into so jittery a frame of mind that but little energy was left to foster technical advances.

Foreign nations had not entered the mad ways of the dictators. Peaceful trading among nations had not given way to conquest by bluff on a show of armed force. Steel for bomb-proof shelters for civilians was not in demand in London. People had some faith in the good intentions of their fellow men, and with that faith they were free to set their minds on the production of better and cheaper goods.

Politicians have had a sorry record in the decade. The metallurgical technicians have had a better one. Improvement in automobiles and aircraft went on apace, with the aid of metallurgical developments like wide strip steel of ultra-deep drawing quality for the former and Al-clad for the latter. Pure zinc made die castings deserve wide acceptance. Welding made huge strides, cast iron rose from a lowly material of construction to one of dignity. High-frequency melting and induction hardening, as well as flame hardening, all grew to commercial importance.

Understanding of precipitation hardening phenomena, of fatigue behavior, of transformations in steel as expressed by the S curve, of the effects of grain size and how to control grain size, of the principles of bright annealing and bright hardening in controlled atmospheres, brought new possibilities and attainments.

Stainless was brought under control and entered the tonnage class. Bright electroplating became a reality. A useful new class of steels, the high yield strength, low alloy group, was created, copper and phosphorus being utilized as strengthening elements. Lead was added to the group of steel alloying elements, making a big step in advance on machinability.

The development of molybdenum high-speed steel materially cheapened that class of cutting tools and in large measure freed us from need for importing tungsten. Carbide tools, in turn, were improved and cheapened. Cadmium and silver became accepted as bases for new classes of bearing metals. Continuous casting appeared on the horizon, powder metallurgy rose a little way over the horizon, and two older processes—copper brazing in hydrogen and metal spray—made advances, though neither one yet has the use it deserves.

One could go on with a very long list of achievements of the metallurgical engineer worthy of citation for the past decade, and there is no lack of others about to emerge from research laboratories to give promise of still greater advances in the next one. The position of metallurgical research has been greatly strengthened, metallurgical executives are increasingly research-minded even though their attention is so often distracted by political turmoil.

The technical societies serving the metallurgical industries have all become stronger and of greater service. Education in metallurgical engineering has had great impetus in the universities, is in capable hands, and assures that the supply of intelligent operators, research men, and sales engineers will continue.

Noteworthy books of metallurgical information

(*Continued on page 226*)

Metals and Alloys Used in

This article is another in a series on the general subject of The Metallurgical Needs of the Non-Metallurgical Industries. There are many manufacturing operations which, while they are essentially non-metallurgical, do make more or less extensive use of metals and alloys. In some cases this involves the use of many alloys or metals, complicated as to composition and properties and involving no little expense—they are essential for the process would not function without them. This article deals with one phase of the large rubber industry—metal molds for tires. Only one plant's practice has been dealt with. To cover the use of metals and alloys in the rubber industry as a whole would require much more space. It is hoped that other discussions may be available later.

The articles of this general nature which METALS AND ALLOYS *has thus far published are listed at the end of this discussion.*

by EDWIN F. CONE

RUBBER TIRES, whether for automobiles, trucks, tractors or even toys are just rubber tires or an everyday manufactured product to the average layman. He sees them roll by in countless variety and size, little realizing that, in their manufacture, certain metals and alloys are almost as essential in the final perfection of the product as the rubber itself.

The writer has been accorded the high privilege by the Goodyear Tire & Rubber Co., Akron, Ohio, of studying the role which certain metals and alloys play, and the extent to which they are essential, in the manufacture of rubber tires. The story is an intensely interesting and revealing one and the following para-

The Largest Rubber Tire Made is 24 x 32. The man is 5½ ft. tall.

Making Rubber Tires

graphs attempt to unfold it. It is confined largely to the tire molds.

A Metal Mold Used

All rubber tires, from the largest to the smallest for automobiles, trucks, tractors and so on, are made in a metal mold. But different tire manufacturers use different molds, particularly with reference to certain features. But so far as the metals and alloys involved in the manufacture of tires are concerned, the metal mold is the starting point. It is in this mold that the contour of the tire—its tread, its side walls and so on, in fact, its appearance and perfection—are regulated and determined. And it is in the metal mold that the vulcanizing or curing is accomplished.

In general it may be pointed out that in the two-part metal mold—top and bottom, or "male and female"—there is placed the plastic chemically mixed and prepared rubber base or compound. Inside this mold the semi-finished, crude appearing, partly formed tire, cylindrical in shape and resembling a small barrel without ends is compressed to the tire size. In it there is placed a bag of rubber similar to but much thicker than an inner tube. Then both are inserted in the mold. While the mold is closed, a pressure of about 250 lbs. per sq. in. is applied to the bag which presses the plastic rubber firmly and completely against the inner lining of the metal mold thus forming the tread, side walls and the final shape of the tire. While this pressure is being applied, the molds in special apparatus are heated to around 300 deg. F. by dry steam. This is the vulcanizing or curing treatment. The final step is to remove the tire from the molds, and use the molds over and over. The tires are of course then subjected to special finishing processes, inspection and so on.

It can be seen from this brief description that the mold must first of all be heavy walled and strong enough to be constantly used under a moderate pressure and temperature without breaking. It should also be emphasized that mold design is a highly important factor to insure a passenger tire, perfectly balanced and in accordance with the latest style. For there are styles or fashions in tires which are constantly changing as in many other products. The Goodyear company maintains a large department devoted only to mold design.

It may appear at first that, from the above general conditions, briefly outlined, the metals required need not necessarily have to meet any especially rigid specifications; need not be alloy steels to meet excessive stresses or to stand high temperatures. But there are certain special conditions to be fulfilled which require careful selection of materials for the molds. Among these may be enumerated: A side wall (the part below the tread) of almost absolute smoothness and uniform thickness, treads that are extremely accurate and uniform in pattern, a mold that is solid and rigid and one that will withstand more than normal pressures and rather rough handling. It is the selection of proper metals and alloys for the molds that insure the results desired.

The Bimetallic Mold

The metal molds, which are the basis of the whole operation of forming and curing the tires, are either bimetallic or not. The Goodyear company claims it is the first one making tires which use a bimetallic mold. By this is meant that inside the outer rim of the main part of the mold a different metal or alloy is used to form or mold the tread. In the single metal mold the patterns, which form the impressions in the rubber for the tread, are engraved or cut in the main metal or steel casting—similar to the preparation of a die of die steel for drop or pressed forgings. It is understood that this is the practice of most of the tire producing companies except Goodyear.

But first, the mold itself, made in two parts, top and bottom, male and female or cope and drag, is of cast steel. They vary in size and weight according to the tire to be made. They are substantially heavy and resemble a flanged bowl some 2 to 4 inches thick.

A High Sulphur Steel Casting

The steel casting used by Goodyear is made by a steel foundry in Akron, the Atlantic Foundry Co., and is an electric furnace product. It is not an alloy steel but it has one unusual characteristic—it is high in sulphur by specification,—0.09 to 0.12 per cent. Since phosphorus has recently become essentially an alloying element in the low alloy, high strength steels, possibly in this steel sulphur might be regarded as an alloying constituent. The composition of the cast steel is as follows:

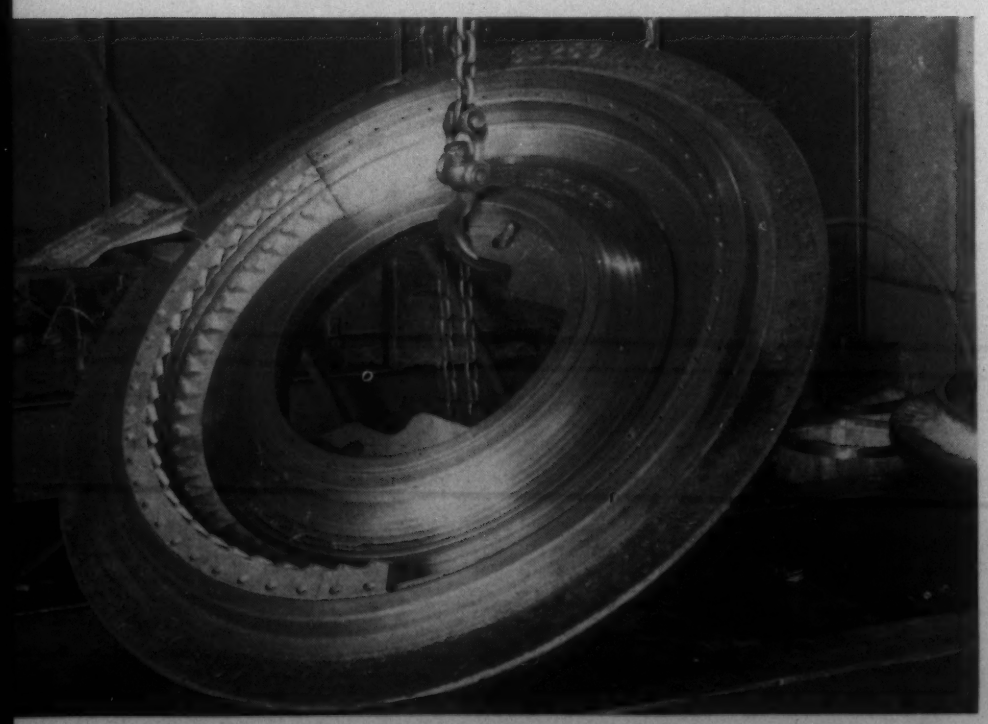
	Per Cent
Carbon	0.22 to 0.28
Manganese	0.75 to 0.85
Silicon	0.45 to 0.50
Phosphorus	0.03 to 0.05
Sulphur	0.09 to 0.12

After normalizing, the tensile strength averages 70,000 lbs. per sq. in. with a yield point of 35,000 lbs. and an elongation of 15 to 20 per cent in 2 in. The castings are used as normalized.

The sulphur is specified abnormally high because it has been found that, in machining the mold, a much smoother and brighter surface can be obtained, particularly in that portion which forms the side walls of the tires. In some cases this surface is smooth and

A Group of Finished Passenger Car Rubber Tires.

A Group of Cast Steel Molds.



A Cast Steel Mold for Passenger Tires, Showing Finished Inside and Some of the Die-Cast Inserts in Place.

for some tires it is fluted. The sulphur also improves the machinability. Each mold section is machined on the inside to the most exacting accuracy. In a large machine shop many types of machine tools are called upon to perform difficult and exacting machining operations.

Aluminum Die Casting Segments

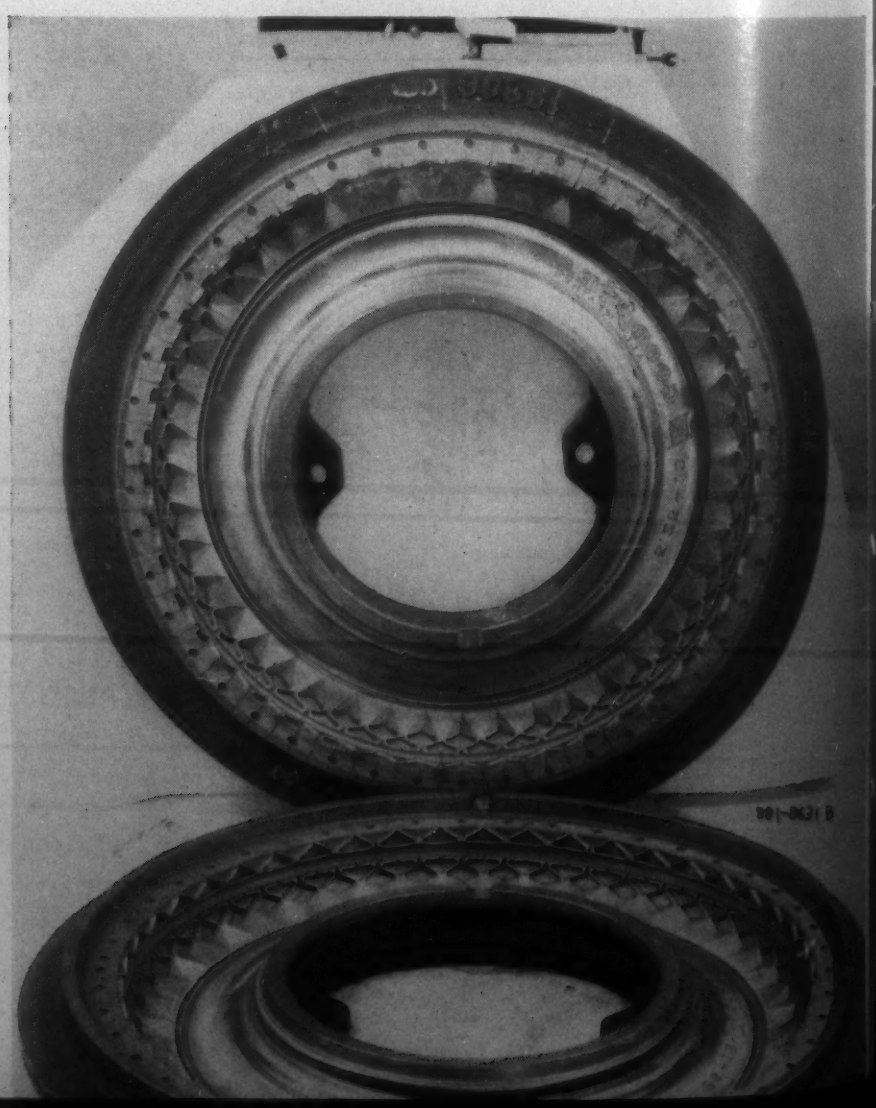
The next step is to prepare that portion of the mold which forms the tread, often complicated in design. In these bimetallic molds the metal which carries the pattern for the tread is a die cast aluminum alloy. These are made in segments of a circle so that in one complete circle there are from 40 to 60 of these in each half mold depending on the size of the mold. These aluminum alloy pieces or segments are from $\frac{3}{8}$ to $\frac{1}{2}$ in. thick. Cast to carefully dimensioned sizes they are machined and fitted into the machined portion of the steel casting so as to form a rigid ring of patterned metal.

The metal selected for this die cast segment is an aluminum alloy, known as No. 13 alloy, of the following composition:

	Per Cent
Silicon	12.00
Iron	0.40
Copper	0.30
Aluminum	Balance

It is melted in gas-fired crucible furnaces and cast in die casting machines in the Goodyear plant. There are now two such machines with another to be installed. The castings are not heat-treated for use. The ultimate tensile strength of this alloy is about 33,000 lbs, per sq. in. with an elongation in 2 in. of 1.3 per cent.

It is evident that when the top and bottom parts of a steel mold, lined on the outer inside edge, are



The Inside of a Complete Passenger Tire Mold with the Tread Forming Inserts in Place.

fastened together, a perfect ring of these die castings is formed below which is the carefully machined steel casting which forms the side walls. In other words there is formed a hollow receptacle which, when the plastic rubber mixture is pressed against it, forms the final contour of the tire—the tread and side walls.

This aluminum alloy was selected for several reasons: Its die casting properties; its freedom from distortion or growth during the uses to which it is put and its permanence. An alloy for use under the exacting conditions must maintain its form, its properties and its original characteristics.

As a rule the aluminum alloy segments have a life longer than necessary because a change in mold design or an alteration in the style of the tread is a frequent occurrence. The used metal is remelted, brought after analysis to its original composition and cast in pigs for re-use.

A Solid Ring of Aluminum Alloy

There is one other type of ring which the Goodyear company employs to form the tread—it is used largely for the large tires and those other than passenger, the type just described being largely for the latter. In the other type the ring is one complete casting made in a sand mold. It is called the Harsch aluminum tread ring as cast by the John Harsch Co., Cleveland. The alloy used is a lower silicon aluminum alloy, No. 43, of the following analysis:

	Per Cent
Copper	0.10
Silicon	4.5 to 6.0
Zinc	0.03
Iron	0.80
Magnesium	0.03
Manganese	0.03
Other	0.03
Aluminum	Balance

This alloy is not heat-treated and in the as-cast condition has a minimum tensile strength of 17,000 lbs. per sq. in. and a minimum elongation in 2 in. of 3.0 per cent. This alloy is made to U. S. Navy specifications, No. 46-A-1-D Class 2. It is understood of course that the pattern for the tread is cast on the inside of this ring. In this case, the used castings are returned to the foundry as scrap for re-melting.

Air bags have been mentioned—the part that resembles an inner tube, but of heavier sections. These are of heavy rubber and are made in cast steel molds. Steel castings also enter into the construction of the pot heaters, part of the vulcanizing apparatus, into which the molds are placed.

A Cast Iron Mold

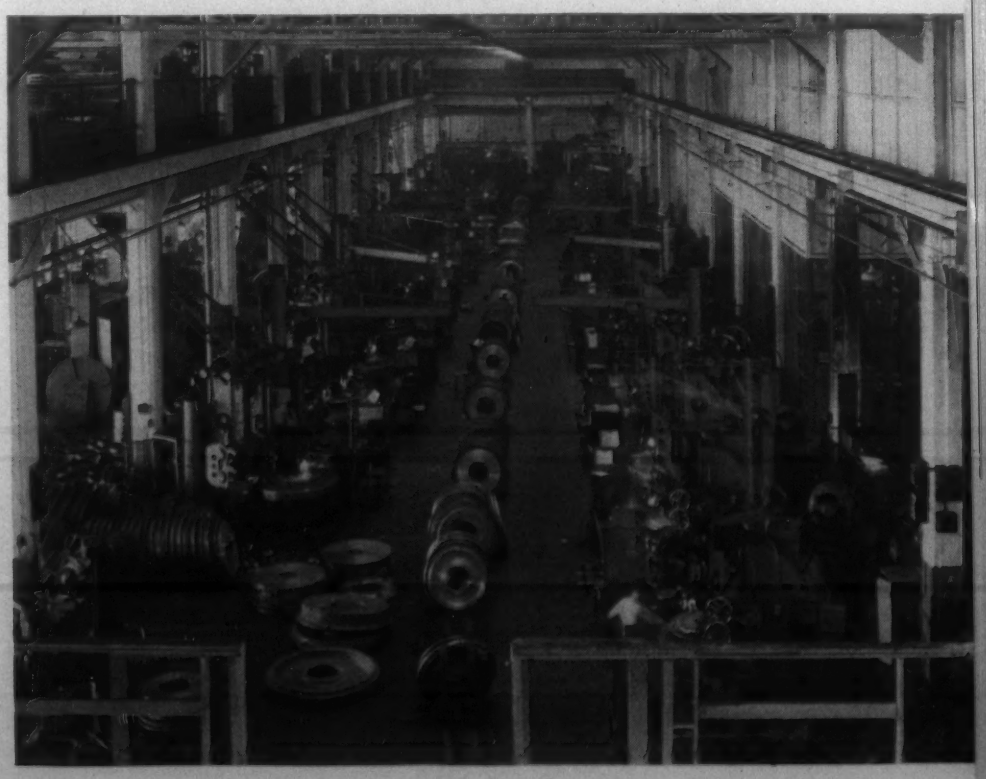
Another type of mold is the steam jacket mold of cast iron. In these are made and vulcanized certain of the larger and possibly cruder or less highly finished tires for tractors, buses and similar equipment. For certain types of tires of this class a cast iron mold is used in place of one of cast steel. The composition of the two types of molds is as follows:

	Jacket Molds	Tire Molds
Silicon	2.10 to 2.30	1.80 to 2.00
Manganese	0.60 to 0.70	0.60 to 0.70
Phosphorus	0.20 to 0.30	0.20 to 0.30
Sulphur	0.08 to 0.10	0.08 to 0.10

For inner tube and life guard molds a grade of iron similar to semi-steel and known as "Sunshine Metal" is used.

Still one other important metal is required in making a tire—the bead wire. This is of course not part of the molds but it is a highly essential part of the tires. The bead is a coil of wire which stiffens and gives strength to the inner circumference of the tire.

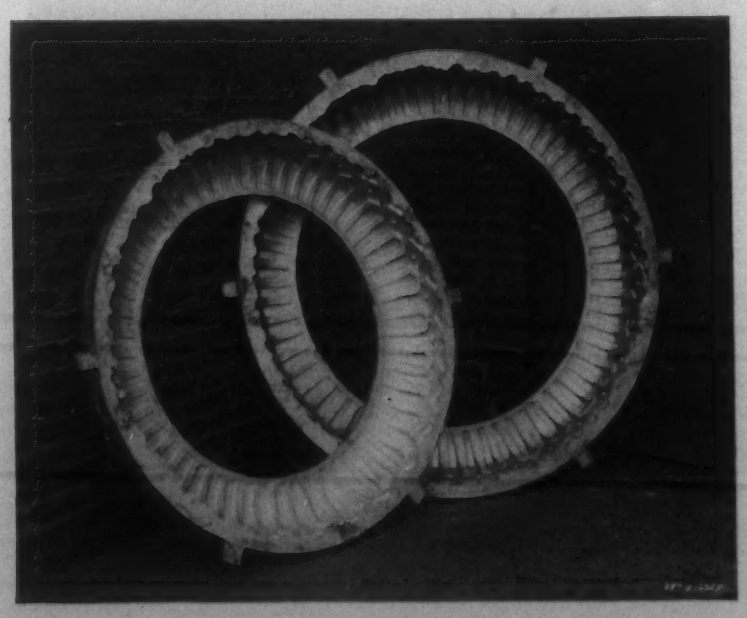
An Insert Die and Its Product.



A General View of the Large Machine Shop in Which the Various Metal Molds for All Types of Tires are Machined.

Inserting an Uncured Tire in a Mold Preparatory to Curing.

A Cured or Vulcanized Tire Ready to be Removed from the Metal Mold after Vulcanizing or Curing.



Solid or One-Piece Cast Aluminum Tread-Forming Rings as Received from the Foundry.

The Die Casting Machine for Making the Aluminum Alloy Inserts with an Insert in the Die.

It is made up of 4, 6 or 8 or more strands of special wire encased in rubberized fabric and joined by special manipulation to the inner rim of the crude tire before vulcanizing.

High Grade Steel Wire for the Bead

Because of the unusual strength which this bead wire must possess and because of the highly stressed conditions it must meet, the metal in the wire must be of the highest grade. The wire used by the Goodyear company is the best grade of piano wire—a high carbon steel. Its physical properties are:

Diameter	0.043 in.
Tensile strength	270,000 lbs. per sq. in.
Elong. in 2 in.	2.75 per cent in 10 in. jaws.
Torsion	45 twists of 8 in. length, under 5 lb. tensile load.

The wire rods are made by the American Steel & Wire Co., subsidiary of the U. S. Steel Corp. The wire is drawn and prepared by the National Standard Co. of Akron. To insure satisfactory adherence of the rubberized covering, the wire is plated with bronze.

Of interest also is the method of imprinting the designations, on the side walls, of the name of the tire, the tire size and so on. This is done by stamping the machined part of the mold with steel stamps.

Such is the story of the metals and alloys used in making rubber tires, both passenger and others. A passenger tire is a highly specialized product. Its uniformity of section and form is of the utmost importance, particularly when a car is traveling at a high speed. This uniformity is largely obtained by selecting the right metals and alloys and in correctly designing and fashioning them into molds.

It is of interest also to record that the molds for passenger and some other tires are prepared in the Akron plant and sent to the company's other tire making units in Canada, Australia, South Africa, the Argentine and so on. Thus in many climes tires of all sizes, from the smallest to the largest—some weighing from 500 to 1,200 lbs. each—are made in metal and alloy molds.

Related Articles in Metals and Alloys

"Special Metals in Oil Field Practice." P. H. Brace. Vol. 5, Sept., 1934, page 181.

"Metals and Alloys in Dentistry." O. E. Harder. Vol. 5, Nov., 1934, page 236.

"Metals and Alloys in the Pulp and Paper Industry." J. D. Miller. Vol. 5, Dec., 1934, page 263.

"Some Metallurgical Aspects of the Radio Tube Industry." Stanton Umbreit. Vol. 6, Oct., 1935, page 273.

"Metallurgical Needs of the Glass Industry." R. D. Smith. Vol. 7, Sept., 1936, page 217; Oct., page 263.

"Metals and Alloys in the Printing Industry." B. W. Gonser and S. Epstein. Vol. 8, Jan., 1937, page 3; Feb., page 59; Mar., page 63; April, page 117.

"Metals and Alloys Used in Diesel Locomotive Cabs." Edwin F. Cone. Vol. 8, Oct. 1937, page 271.

"Metals and Alloys in Aerial Cameras." Edwin F. Cone. Vol. 10, Feb., 1939, page 33.

Fatigue Problems in the Aircraft Industry

by KARL ARNSTEIN AND E. L. SHAW

Goodyear-Zeppelin Corp., Akron, Ohio

This article is the second in a series of six on Fatigue of Metals, the first of which was published in our issues of May and June. The origin and general scope of the series were fully outlined in an introductory statement to the first installment of the first article—"Fatigue of Metals—Developments in the United States"—published in the May issue, pages 158 to 162.—The Editors.

IN NON-AERONAUTICAL BRANCHES, most designs are based to a large extent on past experience. If dynamic loading is prevalent, the designer is usually concerned with making the part in question stand an infinite number of stress cycles of a certain magnitude.

In the aircraft industry the conditions are quite different. The rapid developments in design and the comparatively short history of the industry, limits the information which can be gained from past experience. Most of the loads on aircraft are of a dynamic nature, but some of them, the most severe, occur only a few times in the life of the craft. The aeronautical engineer, due to the great demand for structural efficiency, must in some degree, classify the magnitude of these loads with their expected occurrence throughout the life of the craft and utilize this in designing the parts. It has been the practice of the aircraft industry to take care of this by a system of load factors or factors of safety which vary for different parts of the craft on the basis of experience interpreted by engineering judgment.

When we consider this situation, the complexity of most aircraft structures, and the fact that there is so little known about the actual aerodynamic disturbances and their frequencies encountered in flight, it is remarkable that so few failures have occurred in which fatigue could be regarded as a possible primary cause. To the best knowledge of the authors, there has never been a fatigue failure of a structural girder in operation of an airship, nor has it been clearly proven that any airplane wing spar failed in service due to fatigue in the ordinary sense.

This does not mean that there are no effects of fatigue in aircraft. There have been fatigue failures of wires and other secondary parts in airships; there also have been some fatigue failures of propellers, shafts, and fittings in airplanes. But it should be emphasized that in the majority of aircraft fatigue failures reported to date, the part has failed due to improper installation and unintentional injury or due to imperfect features in detail design, particularly in the early stages of its development.

It has been mentioned that most of the important loads on aircraft are of a dynamic nature. Consequently, all parts of the craft are, to some extent, subjected to repeated or alternating stresses originating from these loading sources. To better understand the possible causes of fatigue phenomena in aircraft, the sources and probable occurrences of dynamic loading[1] and the contributing factors which produce and accelerate fatigue, will be classified as follows:

Sources Producing Dynamic Loads on Parts of an Aircraft

The sources of dynamic loading in aircraft parts may be divided into two classifications: Cyclic and Non-cyclic load variations.

Cyclic loads usually come from the engine and propeller, or from parts of the craft that flutter. Vibrations coming from the engine may be due to unbalanced rotating or reciprocating parts or from fluctuations in the torque reaction. These vibrations are so great in number throughout the life of the craft that they may be considered as infinite. Their effect on the craft's structure can be controlled by a reduction of the unbalance; through the use of flexible mountings, damping, and by avoiding resonant response of the structure.

Propeller vibrations may be due to unbalance,

Fig. 1. Resonance Fatique Testing Equipment.

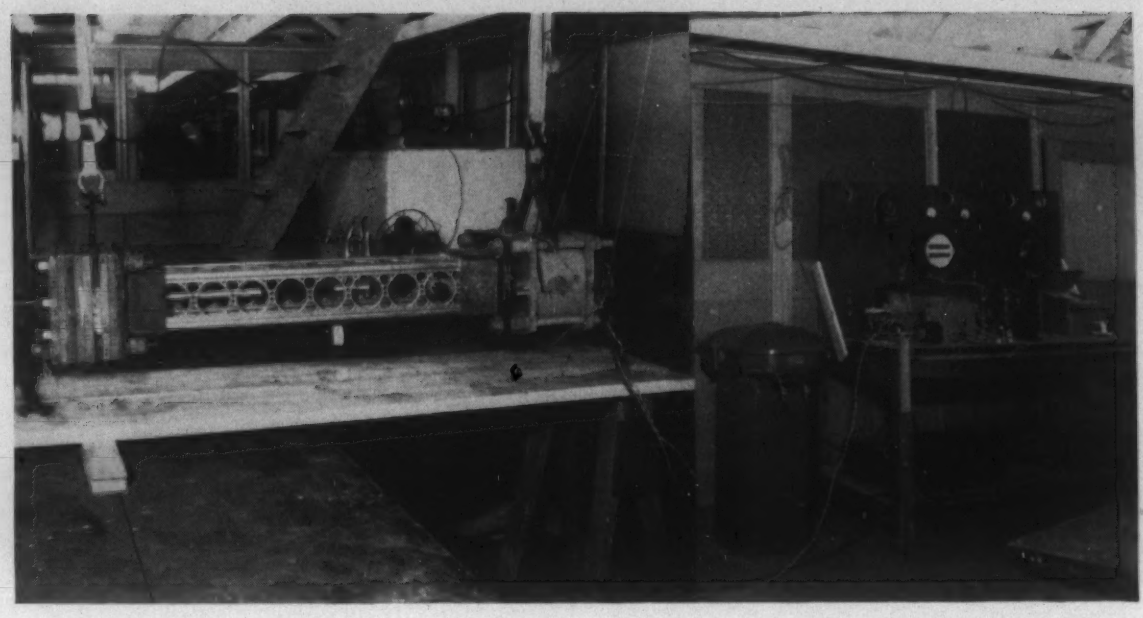
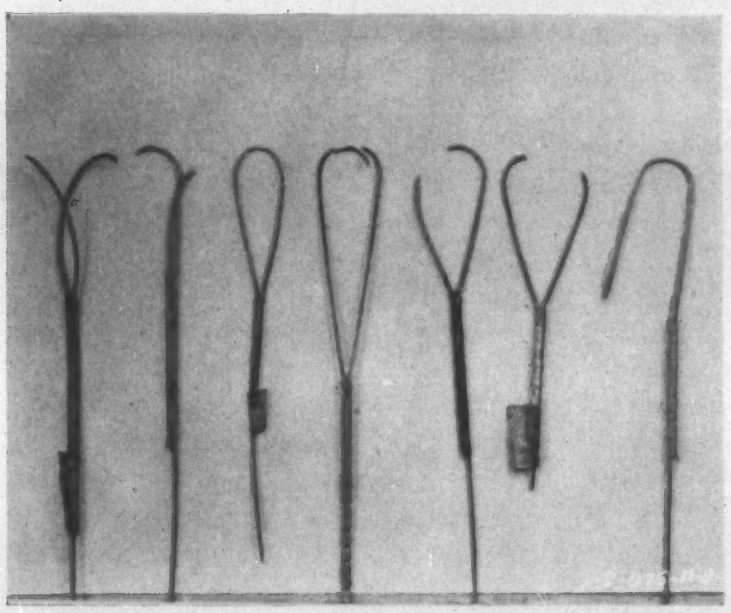


Fig. 2. Test Fatigue Failures in Wire Loops.



unequal pitch, interference, cross winds, gyroscopic effect and flutter. The vibration due to the first two sources affect the structure similarly to those of the motor and may be controlled in the same manner. In the case of interference, relocation of the propeller or interfering parts should be considered. The cross-wind and gyroscopic effect of two-bladed propellers occur only in maneuvers and atmospheric disturbances. The probable number of these vibrations depend upon the type of craft, and mode of operation. The most effective way of controlling these vibrations is to use three or more blades.

Flutter may be described as a vibrating condition of propellers, wings or tail surfaces caused by the simultaneous presence of aerodynamic forces and two or more degrees of freedom to swing. Kuessner[2] of the German D.V.L. reports on two types of wing flutter. One, the less serious from the standpoint of high loading occurs at critical speeds of the aircraft. This type of flutter might have fatigue implications in view of the large number of vibrations that may occur. This may be easily controlled in flight by avoiding the critical velocities or corrected fundamentally by changing the elastic characteristics of the parts so that the critical speed is out of the operating range of the craft. The other, the more dangerous type which occurs at or above a critical speed, may draw energy from the airstream and lead to resonating oscillations which may result in failure. This type of flutter need not necessarily be considered from the standpoint of fatigue proper because the failure is due to excessive stress and has therefore, not been made a part of the scope of this paper. A somewhat different classification of types of flutter is given by Pugsley, J. R. Aero. S., November, 1937.

A vibrating condition known as "buffeting" may be classed as a cyclic vibration, although it is usually non-cyclic in origin. It is defined as an irregular more or less severe oscillation of the tail unit, in which the tailplane bends up and down and the elevators move in an erratic manner. The Committee of the British Air Ministry[3] (investigating an accident of a Junkers aeroplane) explained this phenomenon as resulting from vortices or eddies breaking away from the wing. This is especially prevalent on some low wing monoplanes when the craft approaches the stalling attitude. The frequency of vibration is appreciably lower than that of the motor and the amplitudes may be reduced by proper fairing of the wing and locating of the tail surfaces.

The *non-cyclic load* variations on aircraft usually come from atmospheric disturbances, maneuvers and unsteady air flow about parts of the craft. The atmospheric disturbances seem to be the big question mark for both airplane and airship designers, not only in relation to load variation, but in relation to critical loads as well. We do know that high loads occur but seldom, whereas the small load variations may be quite frequent, although not nearly so frequent as engine vibrations.

The load variations experienced in maneuvering are somewhat predictable and their frequency of occurrence, which is relatively small compared to

that of other non-cyclic loads, depends largely upon the type and usage of the craft. Load variations due to unsteady air flow are caused by vortices or eddies coming from wings, propellers, or other parts of the craft. These loads (like the atmospheric disturbances) are hard to predict both as to magnitude and frequency of occurrence. Their control can be affected only by the better fairing and locating of these parts.

Factors Which Cause Local Increase in Stress and Contribute to Fatigue

Other factors which influence fatigue can be classified according to their sphere of control.

1. The physical characteristics of the material which may be controlled by the metallurgist.

2. Residual stresses, surface finish and inclusions which are controlled by manufacturing conditions.

3. Stress concentration due to discontinuities in cross-section and shape which may be controlled by the designer.

4. Corrosion fatigue and the lowering of strength by heat or injury which are controlled by service conditions.

The effect of these factors in the presence of dynamic loading is beyond the scope of this paper to be discussed in detail. They are enumerated here because of their great importance in aircraft fatigue problems. Although there seems to be no evidence of fatigue failure in an airship girder or a wing spar in the past, this does not show how far such parts may have been from failure or how new trends in design or material may affect this question. A rational study of this problem would involve two parts. First, we must determine the probable life history in respect to loads and their variations on representative parts of an aircraft in actual service. Second, we must study the effect of such stress histories on the parts concerned.

The first part is doubtless the most difficult. An analysis of the source of stress variation may disclose to some extent the frequency of the loads expected on a local part during the life of the craft. However, the range of such variations in load is almost impossible to predict theoretically.

In our opinion, the only feasible way of getting this information is by the installation of self-recording instruments in a craft engaged in regular operation. Recording accelerometer and pressure instruments have been used for this purpose by the American N.A.C.A. and the German D.V.L., and from these data some estimate of stress variations can be obtained. Kuessner[4] uses the mathematical theory of probability in extrapolating data of this nature to predict the expected interval between statically critical conditions. Presumably similar methods would be useful for predicting the probable life of various parts from the standpoint of fatigue. Dr. DeForest's scratch strain gage has possibilities for furnishing stress histories of members but only over limited periods of time. Luftschiffbau Zeppelin (The German Zeppelin Co.) made an attempt to collect such data in actual flight operations at a few strategic points on the "Hindenburg." They used a self-recording instrument of D.V.L. design which to our knowledge, was not used continuously. The records of such an instrument are very detailed and require much time to analyze.

The ideal instrument for this purpose should record directly the maximum tensile and compressive stresses ever reached, and the number of cycles of several different ranges of stresses. It should be completely automatic and not interfere with the normal operation of the craft. It should be connected at all times and not require attention more than a few times a year. It also must be reasonably cheap, light, and accessible so that a number of them can be used without excessive expense.

At the present time the Goodyear-Zeppelin Corp., is attempting to develop an instrument for the U. S. Navy Department to approach these requirements. The principle of this instrument as suggested by Dr. L. H. Donnell, is to utilize the strain in the member to actuate a number of ratchets attached to counters. By properly choosing the size of the ratchet or the mechanical advantage, each counter records the number of fluctuations in a particular stress range. From the individual counter readings, the number of fluctuations of each range is determined. If a gage length

Fig. 3. Wire Loops Fitted to a Grommet.

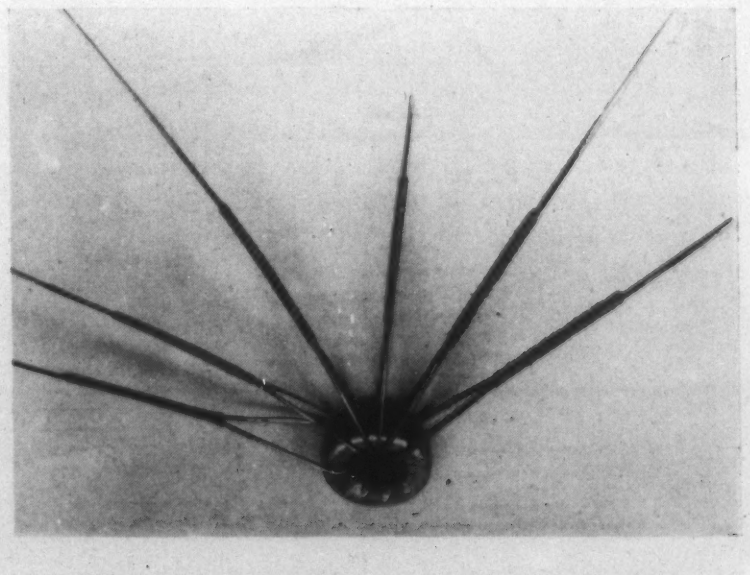
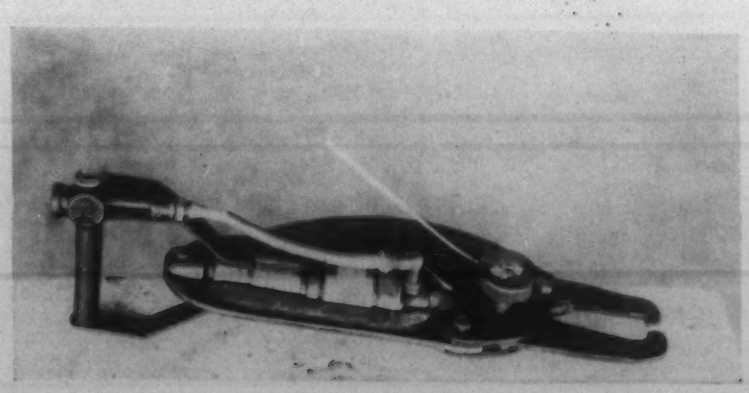


Fig. 4. Automatic Wire-Loop Hammer.



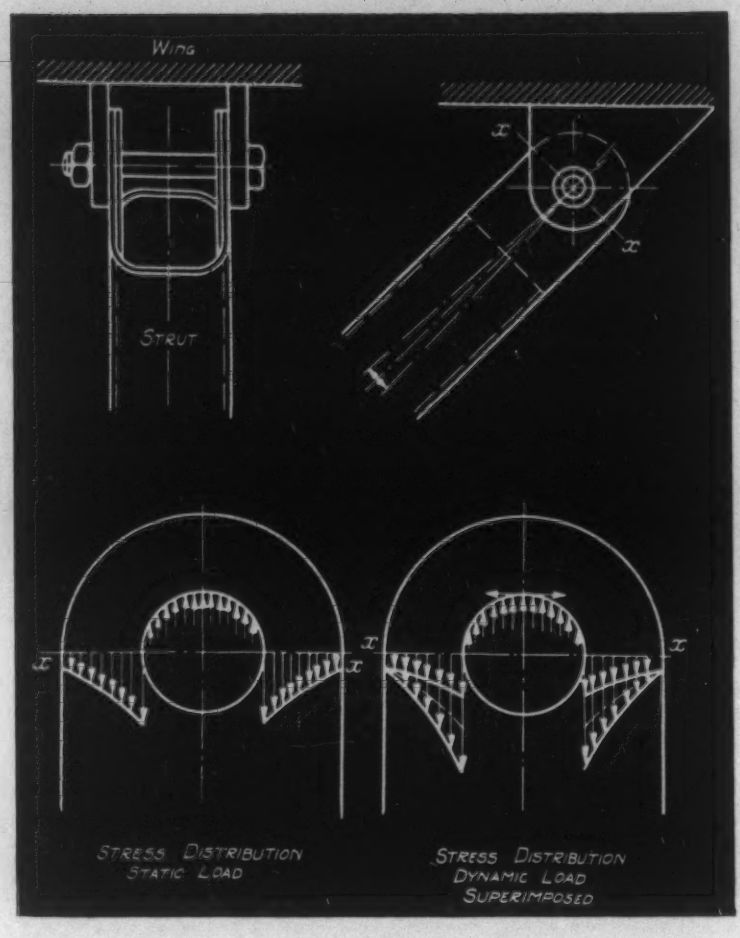


Fig. 5. Wing and Strut Fitting.

is 50 in. on aluminum alloy members, variations in stresses of a few 1000 lbs. per sq. in. can be recorded practically without amplification. A maximum tensile and compressive strain recorder consisting of a simple friction device which slides on a scaled wire or rod is included in the instrument.

The second part of our problem, the effect of such combinations on the fatigue resistance of the structures can best be answered by experimental exploration with accelerated fatigue tests in the laboratory. These tests should lead to some rational or empirical method for predicting the life of a member under such conditions.

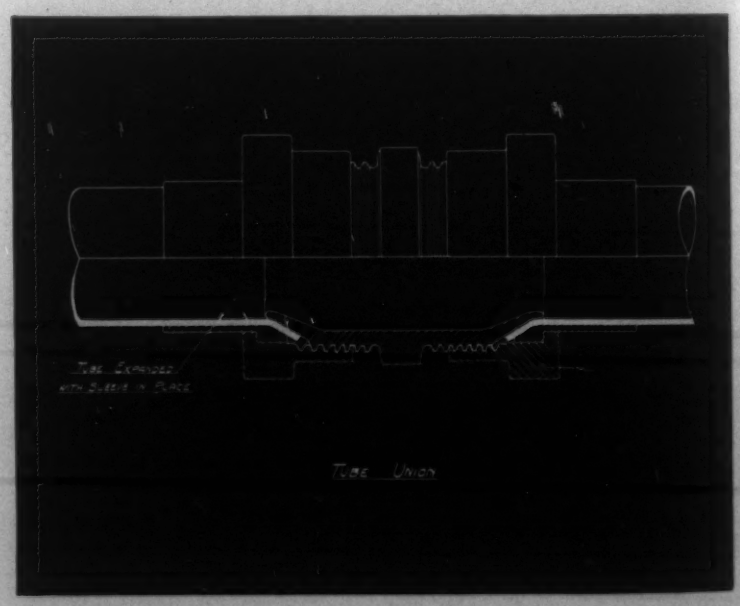
Fatigue Problems of Girders, Spars, and Struts

In girders of composite construction in which several elements paralleling each other are joined together by riveting or welding, the rivets or welds may produce appreciable stress concentrations or notch effects. Where the mutual support between booms is concentrated in individual lattices which are usually shear carriers, a load on the girder will cause secondary forces in the lattices, which will in turn impart secondary stresses to the booms. These may enhance the effect of the presence of the rivets or welds. In girders having booms with perforations, lightening holes, indentations, webbings or other regularly repeated variations in cross sections, there is a complex flow of stress around such holes or recesses accompanied by stress concentrations. It would be very difficult to determine the fatigue behavior of composite girders under all possible loading conditions. However, it is our belief that even a few systematically selected tests may teach lessons of fundamental significance for rational design.

With this in mind, Dr. W. B. Klemperer and R. A. Hudson of the Goodyear-Zeppelin Corp., with the help of Westinghouse engineers, developed a resonance fatigue machine for testing airship girders under axial load cycles (See Fig. 1). The machine consists of two heavy weights connected to each other by means of the test girder and a solenoid motor and control which maintains forced vibrations at resonance with the fundamental frequency of the specimen-and-mass system. The frequency can be controlled by varying the masses and the length of the specimens. The amplitude of vibration is held at any desired amount by the electric control and power input. The results from these tests made up to date have been enlightening and it is felt that this information can be used to better utilize the weight and build structural elements even more efficient, if greater resistance to fatigue, should appear necessary in the future.

Stress-number of cycles results for various types of aircraft girders tested in our Resonance machine and some in our Amsler and Rotating beam machines, confirm the earlier findings of the German D.V.L.[5] (who investigated airplane spars) that the inherent fatigue strength of the metal is never fully realized in a fabricated structure. At present the conventional design of aircraft girders requires riveting or welding in joining the girder elements. If such methods of joining are used the fatigue strength of these connections rather than the fatigue strength of the material in some idealized form is evidently the upper limit which good design may hope to achieve. The classical solution for a round hole in a large plate suggests a stress concentration factor of 3 and a digest of available fatigue tests indicates that just

Fig. 6. Fuel Line Tube Union.



about this factor can be expected between the fatigue strength of metal aircraft girders or joints of present design and the idealized material.

Wire Fatigue Problems

In airships there are a great number of individual wires of various lengths. For practical reasons, airship engineers developed special loop terminals for the connection of the high tensile cold drawn wires. There have been, particularly in earlier designs, fatigue failures in the loops near places where the wire was subjected to variations in stress, especially if associated with slackness of wires. It should be mentioned, however, that with the vast number of redundant wires in the structure, it was overwhelmingly improbable that sufficient wires may fail at any one time to weaken the structure.

Investigations of a few loops that failed in service were made in 1928 by the Bureau of Standards under Dr. L. B. Tuckerman.[6] The following is quoted from a report of their findings:

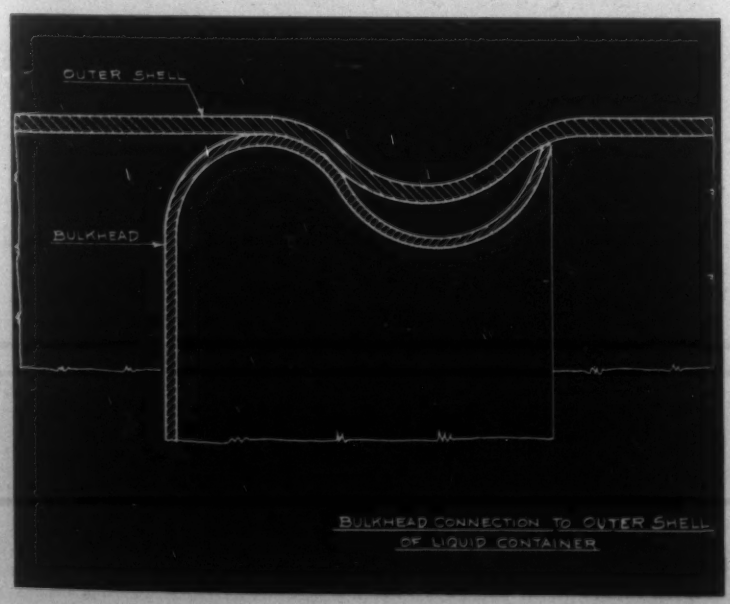
> The routine physical tests, the visual and metallographic examination all indicate that the service breaks are not caused by defective material, nor by excessive tensile stresses, but are flexural fatigue breaks caused by repeated large variations in bending stresses.

The results of this investigation and of other tests (Fig. 2) carried on at the Goodyear-Zeppelin Corp., emphasized the importance of forming the loop to fit the grommet more closely. (Fig. 3).

After a great deal of research in preforming of loops, it was realized that the tolerances required to obtain good results were too close to be practical. It was then found by P. Field, of the Goodyear-Zeppelin Corp., that hammering the wire against the grommets after forming fulfilled the requirements. Subsequent fatigue tests found the hammered loops to develop almost 100 per cent efficiency, it being possible to break the wire outside the loop, though occasionally failure occurred at the edge of the soldered splice where stress concentration would be expected.

The results of this development were sufficiently encouraging to warrant hammering of wire loops in an airship in locations where wire breakage was most likely to occur, a special pneumatic hammer, (Fig. 4), being developed for the purpose. This practice has been proven fully successful in actual application.

Fig. 7. Bulkhead Connection to Outer Shell of Liquid Container.



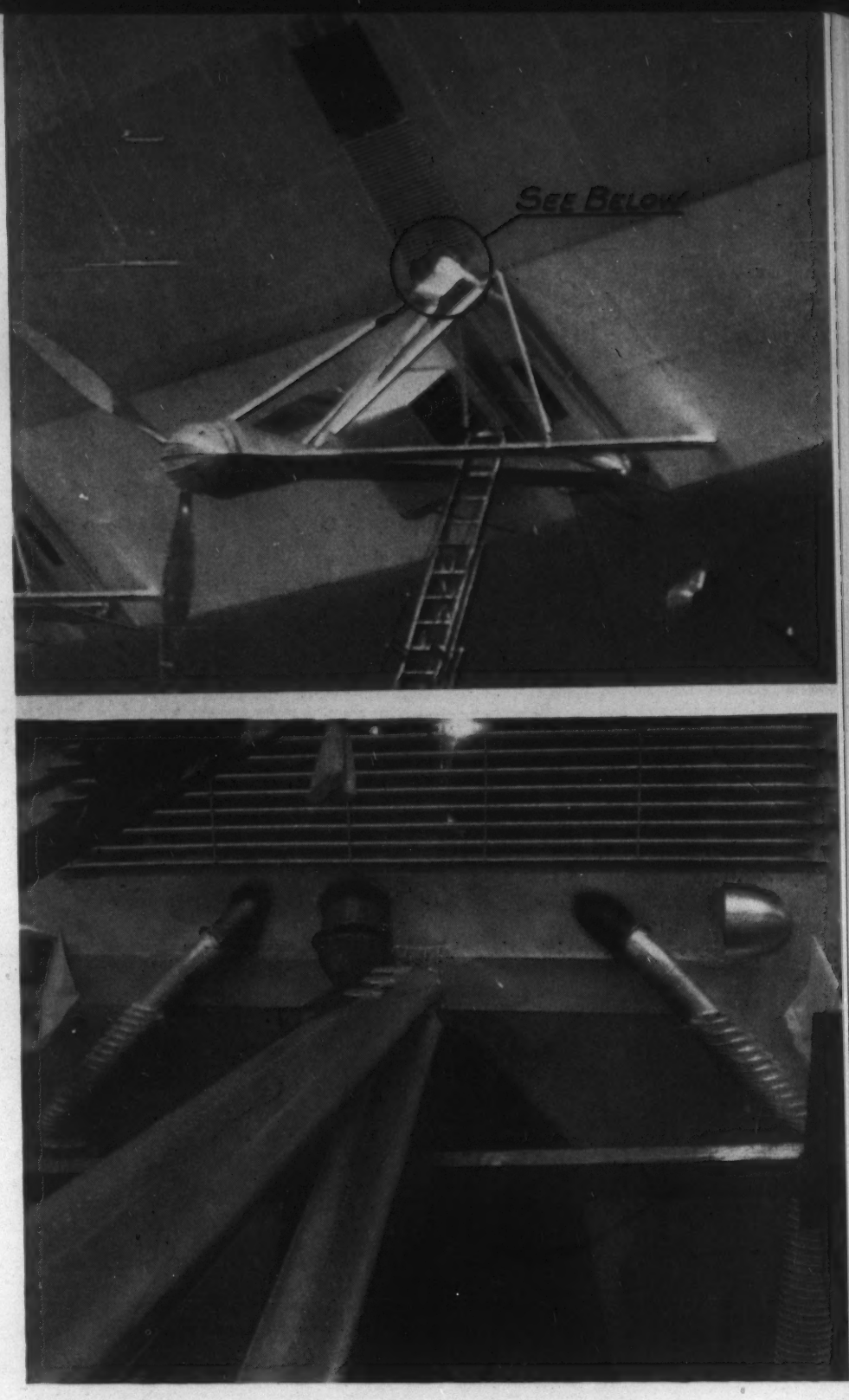


Fig. 8. Exhaust Gas and Water Recovery Cooling Elements.

Cable, Pulley, Joints and Fitting Problems

The fatigue of cables, accelerated by wear and other conditions, has caused some trouble in the past. This problem can be controlled by properly choosing the shape of the groove, the diameter and the material of the sheave. Investigators have found that the criti-

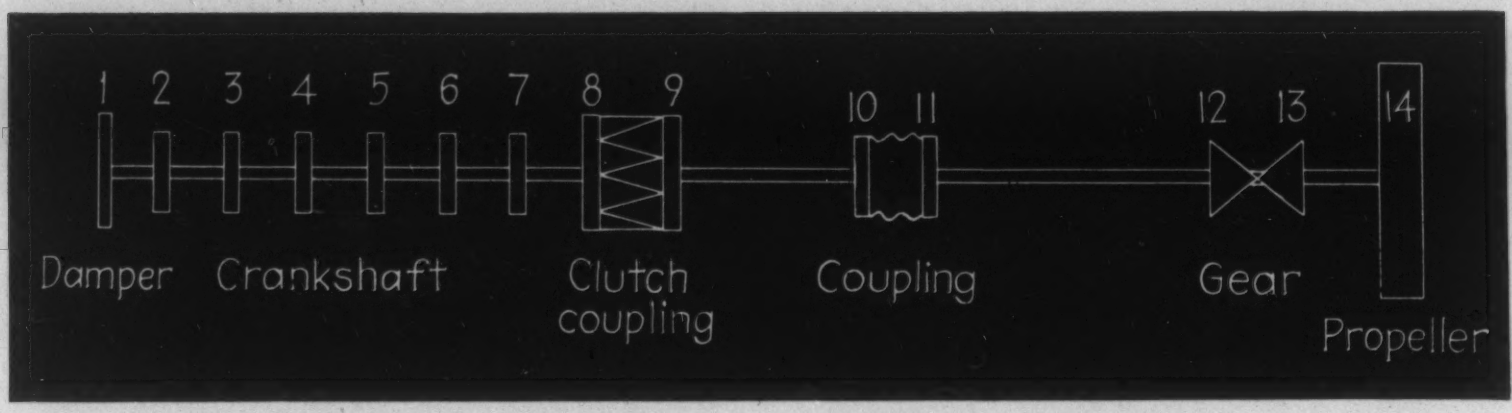


Fig. 9. Diagrammatic Arrangement of Propeller Drive System.

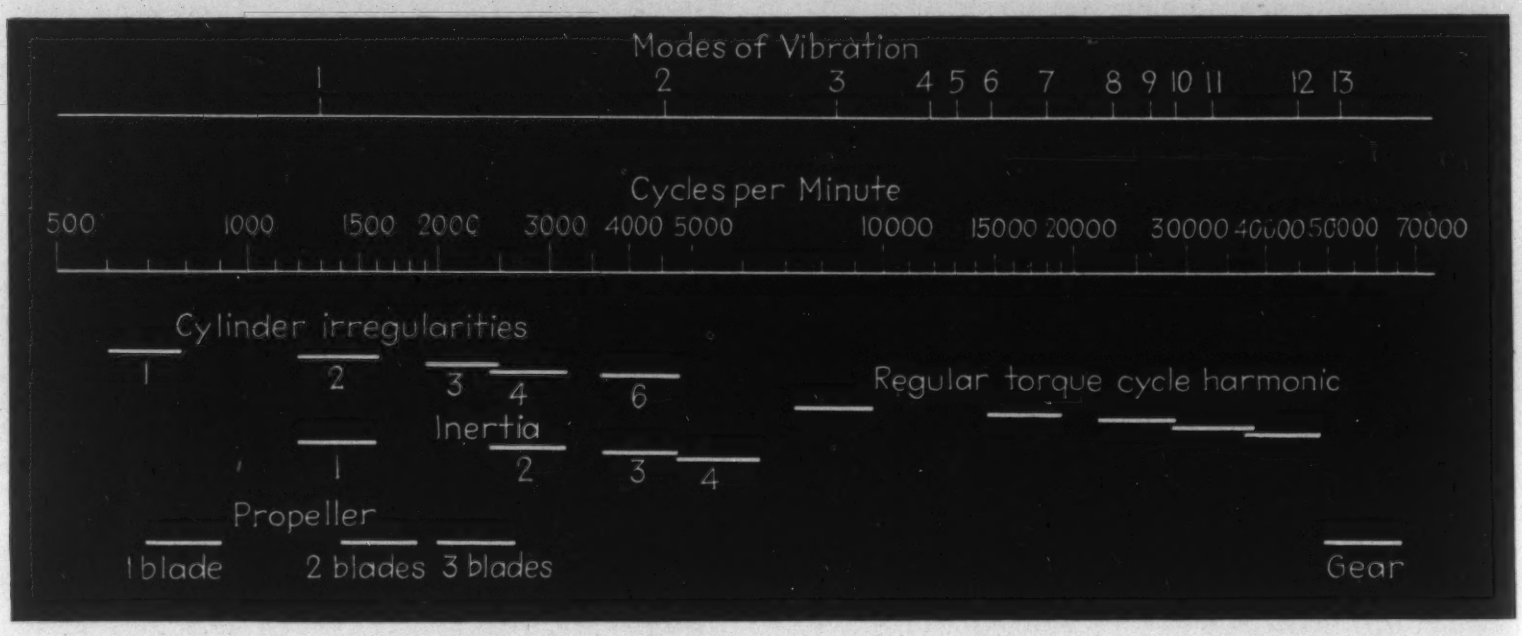

Modes of Vibration
1 2 3 4 5 6 7 8 9 10 11 12 13
Cycles per Minute
500 1000 1500 2000 3000 4000 5000 10000 15000 20000 30000 40000 50000 70000
Cylinder irregularities
1 2 3 4 6
Inertia
1 2 3 4
Regular torque cycle harmonic
Propeller
1 blade
2 blades
3 blades
Gear

Fig. 10. Vibration Excitation Frequency Bands.

cal diameter of the sheave is a function of the stiffness of the cable and has little bearing on the amount of circumferential contact between the cable and sheave.

The problem of efficiently joining structural parts together to develop the full strength of the members has always been one of a complex nature. This should be particularly true from the standpoint of fatigue, for, the practical compromise in design always introduces points of stress concentration due to eccentricities and discontinuities in cross section and shape.

In spite of these practical complications, there have been no fatigue failures of joints reported, and only a few cases where fittings have failed. One in particular that occurred on a German airplane[7] was a case of a hinge and pin type fitting at the end of a strut (Fig. 5). Due to the vibrations of the struts, wear was effected between the pin and the eye, causing high stress concentrations that precipitated cracks.

Another design detail for fatigue consideration was the joint in fuel lines of aircraft and a special testing machine for the flexing of fuel line tubes and fittings under internal pressure was set up in the laboratory of the Goodyear-Zeppelin Corp. The critical section was found at the point where the coupling sleeve forces the flanged tube against the olive union. The weakness was eliminated by expanding the tube against the wall of the coupling sleeve, (See Fig. 6).

Container Problems

The requirements for aircraft liquid containers, are that they must be light in weight, must not leak and yet must be strong enough to accommodate static and dynamic stresses. Various methods of fabrication, including all kinds of riveting, soldering, brazing, and gas, seam and spot welding have been used with varying degrees of success. In large tanks it is generally desirable to provide baffle plates to stiffen the structure and to reduce surging. These may, however, be a source of trouble because of the stress concentrations introduced.

An interesting failure occurred on an airship liquid container, which shows the influence of corrosion and faulty detail construction on the fatigue strength. To avoid high stress concentration and local weakness

due to welding, the baffle bulkheads were rolled into place as shown in Fig. 7. A difference in the properties of the material used for baffles and the outer shell together with imperfect manufacturing procedure permitted a sharp edge to bear against the shell. This circumstance together with the presence of some clearance between shell and bulkhead caused chafing and destroyed the protective surface. Corrosion attacked these places and accelerated fatigue which finally resulted in a circumferential crack at the bottom of the tank. This problem was solved by changing the material of the baffle plate and by properly fitting the bulkhead to the shell.

Another problem, especially in airships, is the handling of exhaust gases. When water recovery is used, the large heat transfer areas of the condenser parts is exposed to not only a large range of operating temperatures, but also to the highly corrosive agents that are present in exhaust gases. To further complicate the problem, irregular shapes are needed to obtain a large cooling surface with low aerodynamic drag, (Fig. 8). The shapes employed may introduce stress concentrations in the presence of pulsating internal pressure and due to the combined influence of these factors, these parts had a relatively short life.

Power Plant Problems

In a propeller drive shaft system in which there is an appreciable length of shafting between the engine and propeller with intermediate couplings and reduction gears, there arises the problem of torsional vibration stresses. If the shaft system be excited at its natural torsional frequency by any source of excitation, the various masses may get into torsional oscillation. Such a condition occurred in the past in one of the German airships, where crankshafts of some of the engines failed. Subsequent investigation showed that the failures were caused by torsional fatigue of the crankshaft. The elastic characteristics of a flexible coupling between the engine and propeller shaft caused the natural frequency of the shaft system to be in resonance at the engine speed.

In the power plants in an airship in which the engines were located inside the hull, the propeller drive system comprised a pair of bevel reduction gears and three lengths of shafting with two elastic couplings, one with a metal spring element and the other with rubber. All told, the system embraced 14 masses separated by 13 lengths of shafting. (Fig. 9).

Torsional vibration tests were made on such an airship power plant and outboard drive system by means of a Geiger torsiograph. From the experiments it was possible to estimate the amount of torsional oscillation stress at various engine speeds in any portion of the shafting. It was learned that while at various engine speeds nearly all of the several modes of the shaft system, (See Fig. 10), were at some time in the range of the various sources of torsional excitation, yet no large amplitude of torsional stress developed. This was undoubtedly due to the damping effect of such parts as the shaft couplings and supports. These test findings were confirmed by flight experience.

Conclusions

Fatigue does not seem to have been an important cause of aircraft failure in the past. No fatigue failure of a primary structural part is known to the authors.

Higher speeds and new materials (particularly with increasing ratio of static to fatigue strength) are introducing new problems.

More knowledge should therefore be acquired of the actual stress variations occurring throughout the life of an aircraft and of the influence of design and fabrication on fatigue strength before we can meet with complete confidence the problems of future development.

Acknowledgment

The authors wish to acknowledge the participation of members of the staff of the Goodyear-Zeppelin Corp., of the Bureau of Aeronautics of the United States Navy Department; and of the Aluminum Co. of America in the various developments which have been referred to in this paper.

References

[1] Constant, Aircraft Vibration. *Journal*, Royal Aeronautical Society, March, 1932.
[2] Kuessner, Fluegelflattern Luftsahrtforschung, No. 6, 1935.
[3] R. & M. No. 1360—Accident to the Aeroplane G-AAZK.
[4] Kuessner, Häufigkeitsbetrachtungen Luftfahrtforschung No. 2 1935.
[5] Hertel, Dynamische Bruchversuche mit Flugzenbauteilen D.V.L. Jahrbuch, 1931.
[6] Tuckerman—Bureau of Standards Laboratory Report, "Broken Wire Terminal Loops." No. 6551, May 10, 1929.
[7] Brenner, Dynamische Festigkeit von Flugzeug-Kontstrucktionsteilen. D.V.L. Jahrbuch, 1929.

The Continuous Welded Rail —An Extended Abstract

BY H. W. GILLETT

THE ASSOCIATION OF AMERICAN RAILROADS is having investigated at the University of Illinois, the properties of the joints in welded rails, with a view to evaluating the various welding methods for making the long, sometimes a mile long, continuous lengths by which end batter, joint troubles and other problems attending short rails, may be avoided. The first progress report, by H. F. Moore, H. R. Thomas and R. E. Cramer has recently been released. It will appear in the *Bulletin of the American Railway Engineering Assn.* The authors emphasize that the report is merely one of progress and that the results are to be taken as tentative.

The rails studied were 131 and 112 lb. rails of 0.70 to 0.73 C, 0.76 to 0.81 Mn, 0.15 to 0.20 per cent Si.

Welding Processes Used

Five welding processes were used:

A. *Gas weld:* Rails torch beveled, welded by two operators, using a rod of about 0.40 C, 1.00 Mn, 0.45 Si, 1.00 per cent Cr; base, web and head welded in that order; time 1½ hr.; top surface peened. After cooling to black, the rail was reheated by acetylene torch to 1600 deg. F. and a magnesia packing placed about the joint, in which the joint cooled to 200 deg. F. in 3 hrs.

B. *Gas weld:* Rails torch beveled, bevel ground free of oxide, welded by one operator in 3 hrs., using rod of about 0.30 C, 1.00 Mn, 0.15 Si, 1.00 Cr, 0.20 per cent V. Welding order: Web, base, head. Head peened several times during welding. Finished weld surrounded with special furnace and heated to 1200 deg. F. for stress relief, cooled in this furnace to 300 deg. F. in 3 hrs.

C. *Thermit weld, usual process:* Weld metal approximately 0.40 C, 0.75 per cent Mn (Al not stated).

D. *Electric flash butt pressure weld:* As described in *Railway Age,* Vol. 103, Sept. 4, 1937, p. 300.

E. *Gas pressure flash butt weld:* Square end rails were forced together by means of an oil pressure cylinder while the ends were heated with many small oxyacetylene flames. As the steel softened, the pressure forced the ends together ⅞ in. forming an upset bead. After cooling below the critical, the joint was again heated above the critical and air-cooled.

All joints were made by commercial organizations expert in the particular type of welding. The joints were ground down as they would be for track service. Hardness surveys of the joint and adjacent metal, deep etch, and metallographic examinations were made. Tension, tension impact, and fatigue specimens were machined from the joints to represent weld metal, weld junction, heat affected zone, and parent metal. The results scatter a good deal and the interested reader should study the original table. By the sub-conscious weighting of the various tests, as the reviewer scans the table, his feeling is that the processes rate in the order: E, D, B, C, and A on the good showing of E, D, and B in fatigue and the rather remarkable ductility in Process E.

However, the properties of the whole weld are of more importance than the indications of specimens cut from it, so endurance tests of the whole joint, under repeated rolling load form a more adequate basis for appraisal. The test developed transverse fissures in welds by Processes A and B, and the apparent high rating of Process B, on the basis of small specimens, is not retained. On the basis of the whole-rail tests, Process D, electric pressure, was indicated to produce joints as good as the original rail, with Process E, pressure, gas-heated, a fair second; Process C, thermit, not bad; but the hand welding Processes A and B show up decidedly poor. Under the drop test, Process D was the only one that gave satisfactory results, with Process E a rather poor second, C a poor third, and A and B entirely out of the running.

If one considers the welding methods, on the basis of probability of oxide inclusions and accidental defects, the results make sense. Whether the requirements of track service demand that welded joints be practically as strong and as sound as the rail itself is perhaps a question, but if one is to be as critical of any part of a continuous length of rail as he would be of any part of an individual rail, the preliminary data strongly indicate to the reviewer that only Process D, electric pressure flash welding, measures up.

That any process can accomplish so good a job as the data indicate for the electric method is quite an achievement.

Rail Investigations of the American Railway Engineering Association at University of Illinois. Fifth Progress Report by H. F. Moore

Abstract by H. W. Gillett

THESE PROGRESS REPORTS are followed with equal interest by railroad men and by metallurgists. They are published both in the *Proceedings* of the A.R.E.A. and in the *Bulletin* of the University of Illinois Engineering Experiment Station.

Hydrogen the Cause of Shatter Cracks

The 5th Report presents more definite evidence along the lines of the tentative indications of earlier reports. Transverse fissures are, of course, the worst-feared fault of rails. The general picture of their genesis is that hydrogen is taken up during melting, collects in certain localities during air-cooling of the rails, exerting enough local pressure to produce shatter cracks whose presence cannot be found by any known non-destructive test.

Under wheel loads of some 40,000 lbs. or over, which stress level is reached now and then in ordinary service, into a transverse fissure, which, when it grows to the size of a dime, can be found in the rail by the Sperry detector car and removed from service. Since the growth from dime size to a rail failure may be very rapid, track detection is a palliative only. Preventing the presence of shatter cracks in the first place is the only way out at present and will still be the best way, even if some adequate non-destructive test for shatter cracks is found that can be applied at the mill.

The hypothesis that hydrogen is the cause for shatter cracks has long been held as plausible, but more definite proof was needed. In the early approach to this problem, solid rails heated in hydrogen gave results tending to strengthen the hydrogen hypothesis, but this evidence was a bit shaky, since the mode of entrance of the gas was quite different from the actual way the gas gets in. Much more definite evidence is presented in the 5th report on the basis of experiments in which hydrogen was bubbled through the ingot as it was being poured. On air-cooling, the rails from hydrogen-treated ingots were lousy with shatter cracks.

Effect of Slow Cooling

The logic of slow-cooling, long known to be helpful in avoiding shatter cracks, thus becomes apparent in that it is a means of allowing hydrogen to escape before the stage of cracking is reached. New experiments showed that in air-cooling the cracking occurs anywhere between 400 deg. F. and room temperature, but that by holding for a long time above that temperature range or cooling at the slow rate of some 8 hr. to pass from 700 to 400 deg. F., the dehydrogenated rail can then be air-cooled from 400 deg.

One might argue that, since only about 1 heat in 50 of air-cooled rails contains enough hydrogen to shatter-crack on air-cooling, the ultimate answer would be to control the open-hearth melt, as by control of combustion, or of slag, to avoid contact of hydrogen with the melt, or to drive out what hydrogen has been taken up by interposing a step of stronger oxidation than in present practice, so that the nuisance of slow cooling would not be required. The investigation does not appear to include any consideration of melting practice, but that doesn't mean that steel makers are not thinking about it.

However, even if one were pretty sure that he could keep hydrogen out of the melt, he would have to retain slow cooling to cover any heat in which the precautions might not have been fully effective, until a non-destructive test is worked out that will catch even the mildest case of shatter cracking. Obviously, the cracks in a shatter-cracked rail would raise its damping capacity, and damping tests offer some promise. The trouble is that some sound rails run a bit higher than the norm for damping, and so far any damping test that could be applied at the moment would scrap good material. An acoustic or "echo" method is to be tried; so all hope for non-destructive testing has not yet been abandoned.

In the line of general testing, the previous idea that a slow-bend test is more discriminatory and revealing than the drop test is amplified and reiterated. To handle all weights of rails, a 600,000-lb. machine is needed. Where the drop test is retained, it should be made head down.

Hardening to Resist Batter

Considerable attention has been paid to the problem of end hardening to resist end batter. Batter is not notably reduced at hardness below 320 Brinell, 35 Rockwell C, while a variety of tests demonstrates that toughness drops very sharply when 47 Rockwell C is exceeded. To be on the safe side, the maximum permissible hardness is set at 415 Brinell, 45 Rockwell C. This is quite in line with the usual metallurgical appraisal of spring-tempered eutectoid steel. The most noteworthy point about the studies of rail steel heat-treated as in end hardening is that the toughness of the lots tested does not vary appreciably between +70 deg. F. and —70 deg. F., while non-heat-treated rails usually drop materially in toughness at sub-zero temperatures.

A CRITICAL REVIEW • PART 3

Grain Size of Steel

(Continued from April)

by N. F. WARD and J. E. DORN

Associate Professor of Mechanical Engineering and Assistant Professor of Mechanical Engineering, Respectively, University of California, Berkeley, Cal. Prof. Dorn was formerly Research Associate at Battelle Memorial Inst., Columbus.

Those phases of the general subject of grain size of steel in which the user—and particularly the heat treater—of steel are primarily interested, are covered in this instalment. The once-mysterious concepts of abnormality and hardenability are simply explained, their relation to heat treating practice discussed, and the effects of austenitic grain size on the service properties of variously heat-treated steels described. Such topics as abnormality among pack-carburized steels, relation of grain size to quench-cracking susceptibility, and adaptability of hardenability information to plant control are covered in useful fashion.—The Editors.

The Effect of Austenitic Grain Size on the Properties of Steels

The effect of austenitic grain size on the "quality" of steel is extremely important from a commercial standpoint. A few years ago it was believed that fine austenitic grains were to be desired for all purposes. It is now well recognized that for some applications coarse austenitic grains have definite advantages. This has resulted in treatments to develop that austenitic grain size which allows the steel to respond most favorably to a given operation [47]. In order to apply the proper heat treatment, it is necessary to know what properties are influenced and how they are influenced by the austenitic grain size. Some of these are given in Table II.

In the austenitic range of temperatures, the size of the austenitic grains influences the properties of a steel in the expected manner. Coarse grained steels, for example, would be expected to deform more readily than fine grained steels at the same temperature. Obviously there is less interference to slip in the coarser grained steels. Correspondingly, coarse grained steels forge more readily than fine grained steels.[30, 37, 49, 84] In addition, as Sanders[49] points out, forgings from coarse grained steels have better fiber structures than those produced from fine grained steels.

Epstein, Mead, and Washburn [38] have observed that the rate of diffusion of carbon into fine grained austenite is less rapid than in coarse grained austenite. The same result was obtained by Rowland and Upthegrove [77] and others [62] in their investigations on decarburization. Sims, in the discussion of Rowland and Upthegrove's paper, suggested that these results may be due to inhibition of diffusion of carbon by the same substance that inhibits austenitic grain growth.

The influence of the austenitic grain size on the properties of annealed or normalized steels may be attributed essentially to the size of the ferrite grains and the size of the ferrite and carbide lamellae of the pearlite patches formed by decomposition of austenite. These factors account for the differences in machinability between coarse and fine grained steels.

In general, coarse grained steels machine more readily than finer grained steels[39], evidently due to their superior chip forming properties. On the other hand, the coarse pearlitic structure causes roughness in the finish and consequently fine austenitic grained steels have a superior finish.

In punch press operations fine grained steels exhibit several advantages over the coarser grained varieties. In blanking they shear "cleaner" and exhibit smaller burrs than the coarser grained steels. In addition, they are less embrittled by cold work[26, 29] and therefore may be drawn deeper and show fewer defects than coarser grained steels [32a]. It is not surprising, then, that they may be subjected to greater reductions in cold rolling [82], etc., than the coarser grained steels. Higher elastic limits and higher

elastic ratios are also associated with finer grained steels [68]. McQuaid [88] has outlined the special advantages of either coarse or fine austenitic grain size in automotive steels.

Shane [50a] and Swinden and Bolsover [78] have thoroughly investigated the influence of austenitic grain size on the properties of steels. They reported that fine austenitic grained steels have slightly low ultimate strengths and yield points. The elongation and reduction in area was found to be only slightly greater for the finer grained steels. Steels with fine austenitic grains, however, had much greater Izod impact values [27, 50a, 78, 85a] than similar steels which had coarser austenitic grains.

Austenitic grain size is also an influencing factor in the creep of steels. Coarse grained steels generally show better creep properties at elevated temperatures, according to Cross and Johnson [34]. This may very likely be an indirect influence due to the size of the ferrite grains and pearlite patches. On the other hand, Clark and White [24, 54, 69] indicate that at lower temperatures fine grained steels have superior creep resistance. These differences have been attributed to a difference in the mode of creep below and above an equi-cohesive temperature. Weaver[100] correlated creep with a vague carbide grain size. In the discussion this was shown to be the austenitic grain size by both Gillett and Aborn. For the most complete correlation between austenitic grain size and creep to date the reader is referred to the recent publication by Cross and Lowther [93a].

Abnormality

It is impossible in this review to consider the problem of abnormality very completely. A great number of papers have been written on this subject and a selected bibliography is given at the end of this paper. (References 2 to 14 inclusive and also 22, 26, 60, 61, 80).

Abnormality is a term now used to describe the micro-structure often found in slowly cooled steels, especially case carburized steels. This structure differs from the so-called normal structure in that the carbide outline of the former austenitic grains is thick and often shows some coalescence (See Fig. 16). Within this thick carbide envelope, which is frequently incomplete due to coalescence, is divorced ferrite. The center of the former austenitic

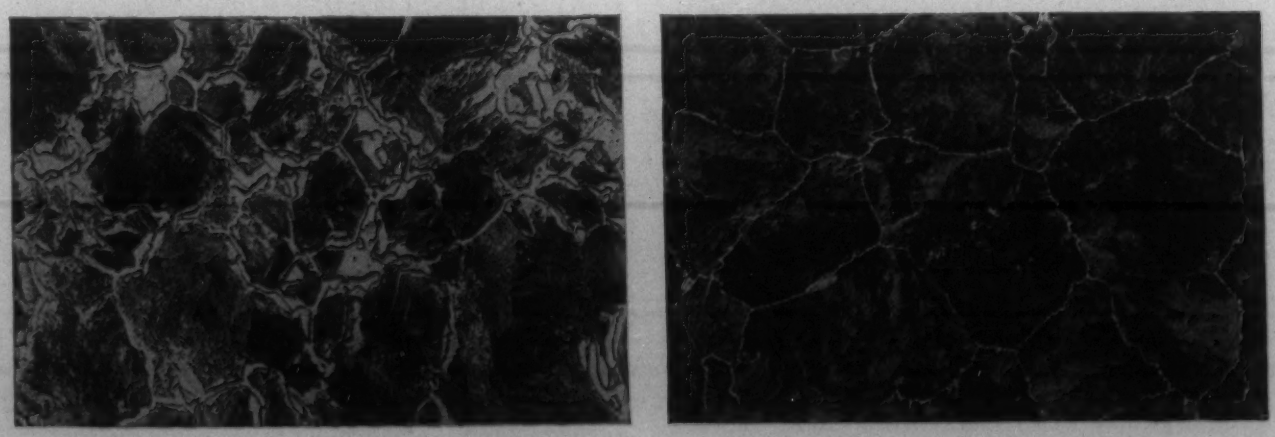
Table II.—Effect of Austenitic Grain Size on the Properties of Steels

	Property	Effect of Finer Austenitic Grains
In the Austenitic Condition	Plastic forming	Poorer forgeability and greater resistance to slip
	Rate of carburizing and decarburizing	Slower
	Rate of decomposition	More rapid
Annealed or Normalized	Machinability	Poorer due to poorer chip forming properties
	Machined surface	Better surface finish
	Blanking	Smaller burrs
	Cold working	Less embrittled, possible to draw deeper and roll more severely
	Elastic ratio	Higher
	Yield point	Slightly lower
	Ultimate strength	Slightly lower
	Elongation	Greater
	Reduction in area	Greater
	Impact resistance	Higher
	Hardness	Lower
	Creep resistance	Better below equi-cohesive temperature Poorer above equi-cohesive temperature
	Normality	Greater tendency toward abnormality
	Difference between annealed and normalized structures	Less
Hardened or Hardened and Tempered	Maximum hardness	Independent of grain size
	Hardenability	Much shallower hardening
	Impact resistance	Much greater
	Quench cracks	Seldom exhibits quench cracks
	Grinding cracks	Seldom shows grinding cracks
	Untransformed austenite	Less austenite retained
	Soft spots	More susceptible to soft spots
	Distortion	Less susceptible
	Internal stresses	Lower

grain may contain no pearlite in extreme cases of abnormality, or, in other cases, a thickened and partly coalesced pearlitic structure. Bain [22] has studied the development of abnormal structures in steels. He found that the carbide envelope forms first, as in the normal structures, but as the temperature is lowered, a pure ferrite rim separates out from the austenitic core. Carbon from the core migrates through the ferrite to the carbide rim causing a thickened rim. Simultaneously, coalescence of the carbide takes place. In extreme cases of abnormality, this continues until practically no carbon remains in the core and pearlite is formed at the center of the previous austenitic grain.

From his experiments, Bain [22] concluded that abnormality was the result of rapid diffusion of carbon in ferrite. In order to develop an abnormal structure it is necessary for the carbon to diffuse through the ferrite more rapidly than the rate at which ferrite itself is being formed. On the other hand, if the carbon cannot diffuse through the ferrite sufficiently rapidly, simultaneous precipitation of ferrite and carbide will occur and the structure will be pear-

Fig. 16. Abnormality in Steel. The photomicrograph on the left represents a coarse-grained abnormal steel, and that on the right shows a coarse-grained normal structure. (Courtesy of H. W. McQuaid)



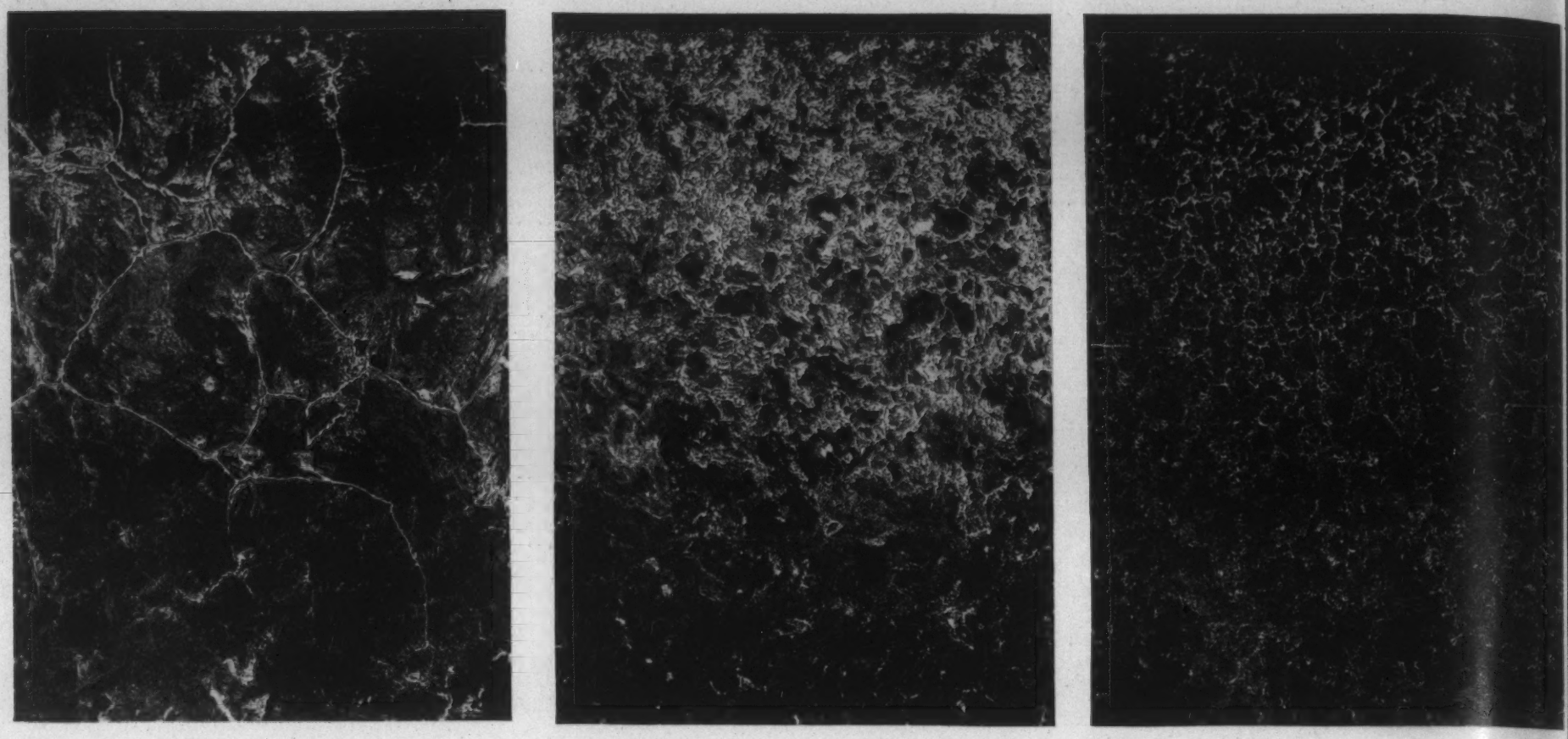


Fig. 16a. Photomicrographs of Case Carburized Steels Demonstrating Some Abnormality Peculiarities, Observed by Lauderdale and Harder in a Paper Presented at the Oct. 1938 Meeting of the American Society for Metals. Micrograph I (Left) illustrates increased tendency toward abnormality in the outer rim of the case of a coarse-grained steel. In II pronounced abnormality in the outer zone is apparent. Micrograph III (Right) illustrates another peculiarity, namely, an outer rim of extremely fine grains. (Courtesy of O. E. Harder)

litic or normal. For this reason, more rapid cooling often reduces the degree of abnormality. Nevertheless, in extreme cases, it causes the presence of soft spots in quenched steels. Fig. 16a illustrates some abnormality peculiarities observed in carburized steels.

Abnormality is not necessarily an "inherent" property of a given heat of steel. It has been found that steels that are pack carburized often exhibit abnormal structures, while the same steels carburized with gases containing no oxygen have definitely normal structures [13]. Obviously the presence of oxygen induces abnormality. There appears to be little agreement, as yet, whether the oxygen need be in the form of oxides or as dissolved oxygen to be efficacious in producing abnormality, although the latter appears more probable. Furthermore, the function of oxides or oxygen in promoting abnormality is still under discussion. Numerous possible explanations have been suggested. The hypotheses that oxygen in ferrite may increase carbon diffusivity [22], or that oxygen raises the transformation temperature [10, 14] or a number of other possibilities [61] have been offered as explanations of its influence on the abnormality of steels.

A discussion of the relative merits of these various theories offered to explain the cause of abnormality is outside the scope of this review. It is interesting to note, however, that abnormality is generally associated with fine grained steels in spite of the fact that rapid rates of transformation would allow less time for the diffusion of carbon through the divorced ferrite. The fact that fine grained steels are generally more highly deoxidized than the coarse grained steels, and therefore have a lower original oxygen content, introduces another paradox. An interesting photomicrograph by Digges [94a] of an annealed high purity iron-carbon alloy (1.21 per cent C) showing extreme abnormality adds to this confusion, especially as spectroscopic analysis of the alloy did not reveal even a trace of aluminum. (See Fig. 17).

Although abnormality is found more frequently among fine grained steels than among coarse grained steels, frequent references to the existence of coarse grained abnormal steels may be found [80]. These indicate that propensity to abnormality is not necessarily the result of the same factors which cause fine grains. Furthermore it is incorrect to describe abnormality as a property of the steel. It may very likely be a result of the carburizing technique.[13, 80, 94] Fig. 17a shows grain size gradations along the cross-section of a carburized steel.

Hardenability

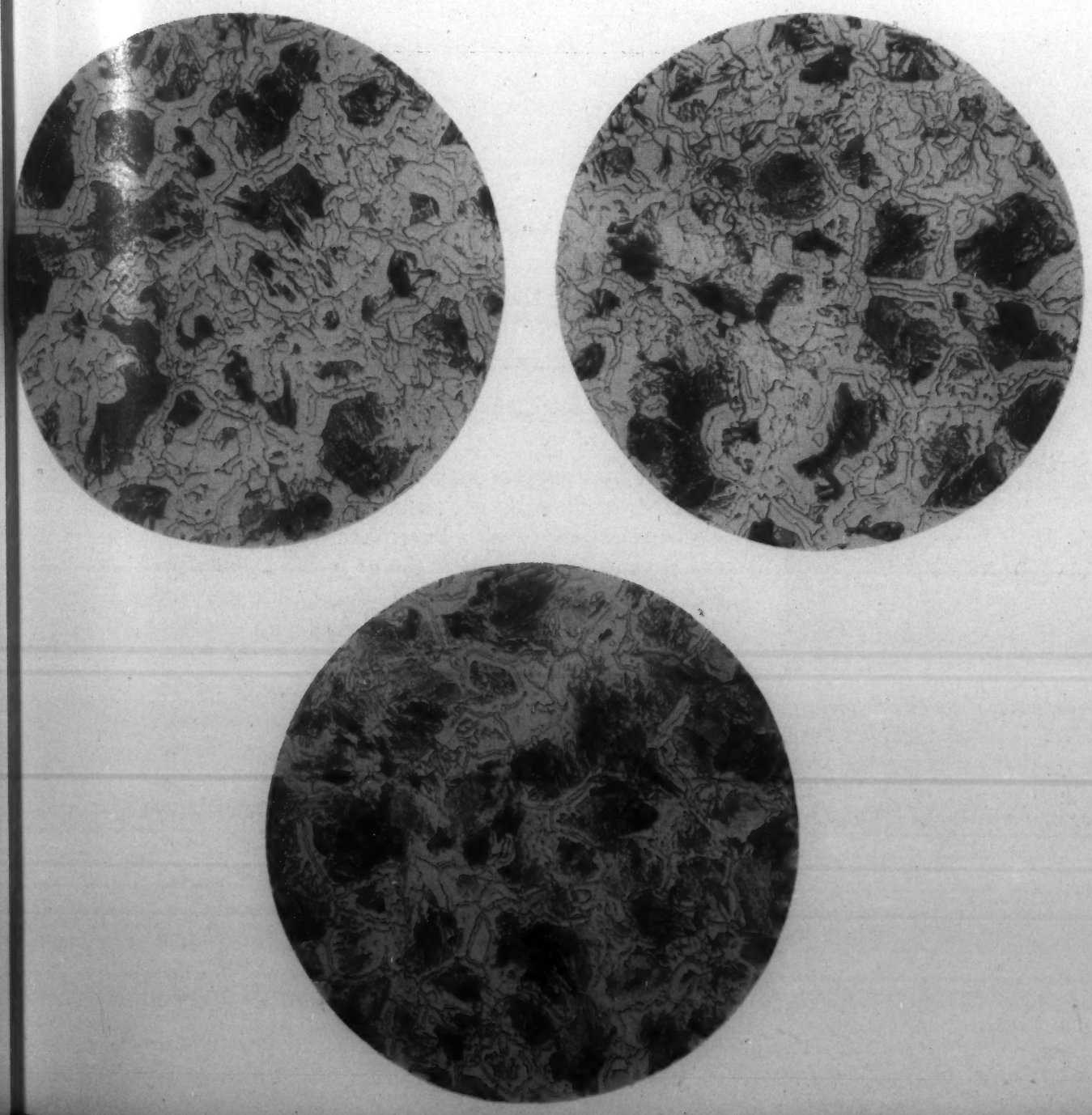
Undoubtedly the properties of quenched steels are more directly related to their austenitic grain size than the properties of the annealed or normalized struc-

tures which were discussed previously. This is especially true of hardenability. According to Burns, Moore, and Archer [93] hardenability is a measure of (a) the maximum hardness attainable, and (b) the penetration or depth of hardening. If a cylinder of steel is quenched from above the upper critical temperature in a medium which cools the outside layer of the cylinder more rapidly than the critical quenching rate, this portion will have the maximum hardness obtainable. The deeper layers cool at slower rates. In some steels, therefore, the rate of cooling the central portion is not sufficiently above the critical quenching rate to develop maximum hardness. In fact the rate of cooling may be below the critical quenching rate, and the hardness of the core will be less than that of the case.

Steels having coarse austenitic grains have relatively long induction periods. The core of cylindrical samples of these steels, therefore, may cool to the low temperatures where martensite forms before the induction period for the formation of pearlite has been completed. Under these conditions the steel hardens to the center of the cylinder. On the other hand, steels that have fine austenitic grains have much shorter induction periods. They begin to transform to ferrite and pearlite in short periods of time. It is quite possible, therefore, that a quench that deeply hardens a steel having coarse austenitic grains will

Fig. 17a. A Composite Photograph of a Case Carburized S. A. E. Steel Investigated by Lauderdale and Harder. A fine-grained outer rim developed; nevertheless, the remainder of the case and also the core had coarser austenitic grains. (Courtesy of O. E. Harder)

Fig. 17. Photomicrographs (below) show Abnormality in Slowly Cooled High Purity Iron-Carbon Alloys. In spite of the absence of aluminum and in spite of the coarse grains (No. 4) the steels below show coalesced carbide envelopes about the former austenitic grains divorced ferrite and thick lamellae in the pearlitic islands. (Courtesy of H. K. Herschman, National Bureau of Standards)



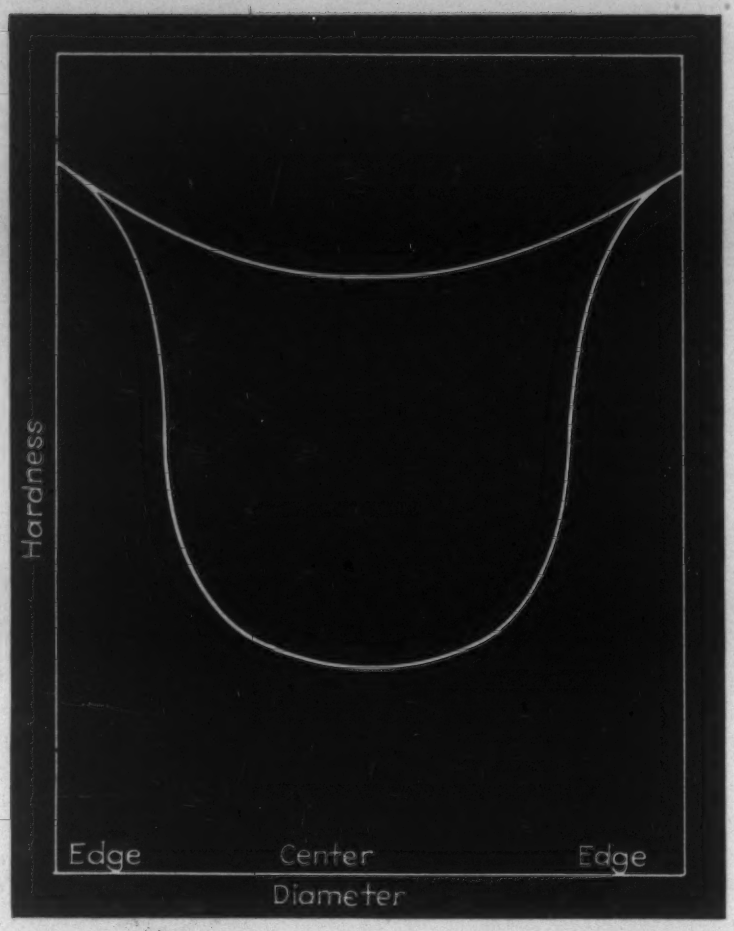


Fig. 18. Curves Illustrating the Variation of Hardenability with Grain Size. The upper curve is a schematic representation of a deep-hardening coarse-grained steel. The lower curve shows the effect of fine grains. The hardness of the core of the test cylinder drops to a very low value. The surface hardness, however, is the same for fine and coarse-grained steels.

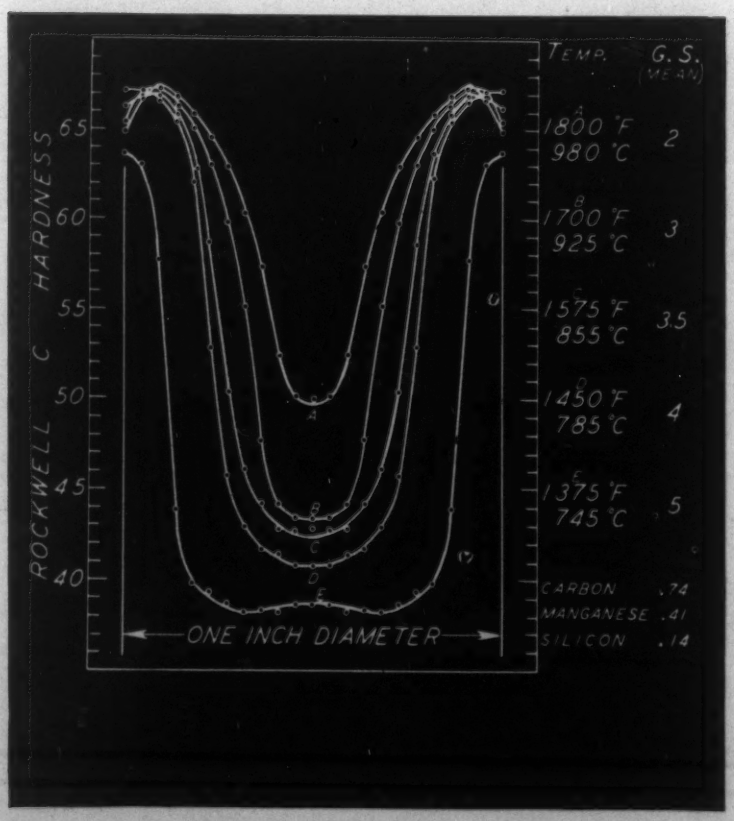


Fig. 19. The Relationship between the Penetration of Hardness of a Quenched Steel Cylinder and its Previous Austenitic Grain Size. As the grain coarsening temperature was raised, larger grains were formed and the steel became deeper hardening. (Courtesy of E. S. Davenport)

completely harden only the case of the same steel when it has fine austenitic grains. The hardness diminishes as the center of the cylinder is approached. Although the quenching rate in the center zones was above the critical rate for the coarse austentic grains, the fine austenitic grains transformed to a softer structure because of their shorter induction period. These effects are illustrated schematically in Fig. 18. Quantitative data are plotted in Fig. 19.

The above explanation of the differences in hardenability was given by Bain [23] as a result of his investigations on rates of transformation and hardenability. In general, steels having fine austenitic grains are shallow hardening, while steels having coarse austenitic grains are deep hardening [19, 46, 51, 52]. Austenitic grain size, however, is only one of many factors that influence hardenability. Alloying elements, which increase the duration of the induction period or decrease the rate of transformation, promote deeper hardening. Davenport and Bain [35] have also shown that solid non-metallic inclusions may function to initiate nucleation of ferrite and hence have the same effect as fine grains on hardenability. Steels that are deoxidized with aluminum for the purpose of inhibiting austenitic grain growth, therefore, often exhibit fine grained characteristics even after the grains are coarsened because of the presence of many points for nucleation throughout the grain, because of the submicroscopic non-metallic inclusions [35]. The effect of mass on hardness penetration in samples of the same steel is snown in Fig. 20.

Several methods of reporting hardness have been used. Some of these have been discussed by Grossman in a recent paper [96]. Shepherd's method [53] is very rapid and requires practically no special equipment. It is particularly adaptable for control in the small plant or shop. Bain [23] employed a graphical method which has the advantage of detailed accuracy. This method has been widely used in theoretical researches as well as in plant control. McBride, Herty, and Mehl [74] modified Bain's method and reported only the numerical result in terms of

$$\text{Relative Hardenability} = \frac{\text{Fraction hardened}}{\text{Fraction unhardened}}$$

This method appears to have some advantages that the other methods do not possess, namely the relative hardenability [27, 43, 74], is a linear function of the quantity S, which was defined as the grain surface area per unit volume. More recently Burns, Moore, and Archer [93] developed a method of reporting quantitative hardenability that is quite similar to the McBride, Herty, and Mehl method. It also has definite advantages over other methods. For a detailed description of these methods, the reader is referred to the original papers.

The above methods of reporting the hardenability were developed because of their adaptability to plant

control. They are not, however, direct determinations of hardenability, but are indirectly associated with the true hardenability. As Davenport and Bain have shown by means of their S curve, any plain carbon steel hardens completely and develops a martensitic structure in a continuous quench, if the rate of quenching from about 1110 deg. F. to about 930 deg. F. exceeds a definite critical rate for the steel in question. Steels that are shallow hardening or, in other words, steels that have low hardenabilities have higher critical quenching rates. The true hardenability of a steel, therefore, is inversely proportional to its critical quenching rate over the range of 1110 deg. F. to 930 deg. F. Expressing this in the form of an equation yields

$$\text{True Hardenability} = \frac{\text{Max. time elapsed to yield martensite}}{\text{Temp. drop in deg. F. (1110-930)}}$$

A recent publication by Digges [94a] on the effect of carbon on the hardenability of high purity iron-carbon alloys was interpreted on the fundamental basis of the critical cooling rate from 1110 deg. F. to 930 deg. F. A series of alloys containing from 0.23 per cent C to 1.21 per cent C were prepared by carburizing vacuum-melted electrolytic iron. All samples were treated to develop a No. 4 grain size and then quenched. Cooling curves and the microstructures were correlated and the critical quenching rate for each alloy of the series was determined. Digges found that the critical quenching rate decreased with increasing carbon concentration. Correlating the results of Digges with the above equation yields

$$\text{True hardenability} = 0.00022 + 0.0011 \times \%\text{C sec./deg. F.}$$

The true hardenability, therefore, increases linearly with the carbon content. It may be anticipated that over a sufficiently narrow range of concentrations, the hardenability of steels with additional elements will vary linearly with the concentration of these elements. Several empirical linear hardenability factors have been proposed in the past with special applications to hardness-penetration plots. [85, 93].

The common methods for determining the hardenability of steels are not readily adapted for application to carburized steels. Jominy and Boegehold[96a], however, developed a method which appears to have certain virtues. A cylindrical specimen, 1 in. in diameter and 2¾ in. high, is carburized and then quenched on the lower face with water. A special jig is employed for quenching. The distance from the quenched end at which the surface hardness (0.015 in. below the cylindrical surface) drops to below 600 Vickers Brinell or 60 Rockwell C is termed the hardenability. Cooling curves of the quench taken at various points along the cylindrical surface demonstrated that the reciprocal of the rate of cooling was a linear function of the distance from the quenched end. It is obvious, therefore, that the distance from the quenched face at which the surface hardness drops below its maximum value is proportional to the critical quenching rate. The hardenability determined by this method appears to differ from the true hardenability by a multiplicative factor. The application of this method to non-carburizing steels should prove valuable.

Toughness is another property of steels that is influenced by the austenitic grain size. (See references 11, 19, 47, 48, 51, 52, 65, 68, 78). It is widely known that the impact resistance or toughness of hardened steels increases as the hardness diminishes. Fine austenitic grained steels are not so hard in the core as coarse austenitic grained steels. Therefore they have tougher cores and resist dynamic stresses to a greater extent than similar deep hardening coarse austenitic grained steels. (See Fig. 21). Fine grained plain carbon steels are frequently used in place of low alloy steels where high toughness and low cost are the important factors. It has frequently been reported that the toughness of normalized or annealed fine austenitic grained steels is also higher than that of coarse austenitic grained steels in the same condition [78].

In general, fine austenitic grained steels seldom, if ever, crack during quenching [21], while coarse grained steels and steels having duplexed coarse grains induce greater expansion on quenching and cause greater warping. Davenport, Roff, and Bain[36] found that the micro-cracks observed in quenched steels re-

Fig. 20. Photographs Illustrating the Variation of the Penetration of Hardness with the Diameter of the Specimen. Samples of an S. A. E. 1045 steel, 3 in., 2 in., 1½ in., 1 in. and ¾ in. in diameter, were quenched in water, cut in half and etched. The light zone is composed of martensite and the dark core of fine pearlite. The rate of cooling of the core did not exceed the critical quenching rate. The larger samples are shallower hardening because of their slower rates of cooling. (Courtesy of R. S. Archer)

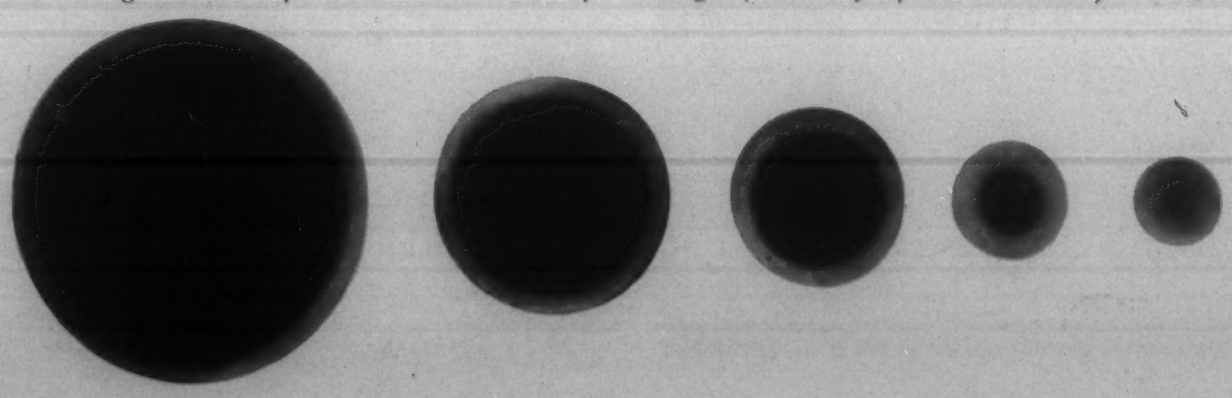


Fig. 22. Graphs Illustrating the Differences in the Physical Properties of a Coarse and a Fine Grained S. A. E. 1040 Steel Quenched from the Temperatures Indicated and Tempered at 1050 deg. F. (Courtesy of P. Schane, Jr.)

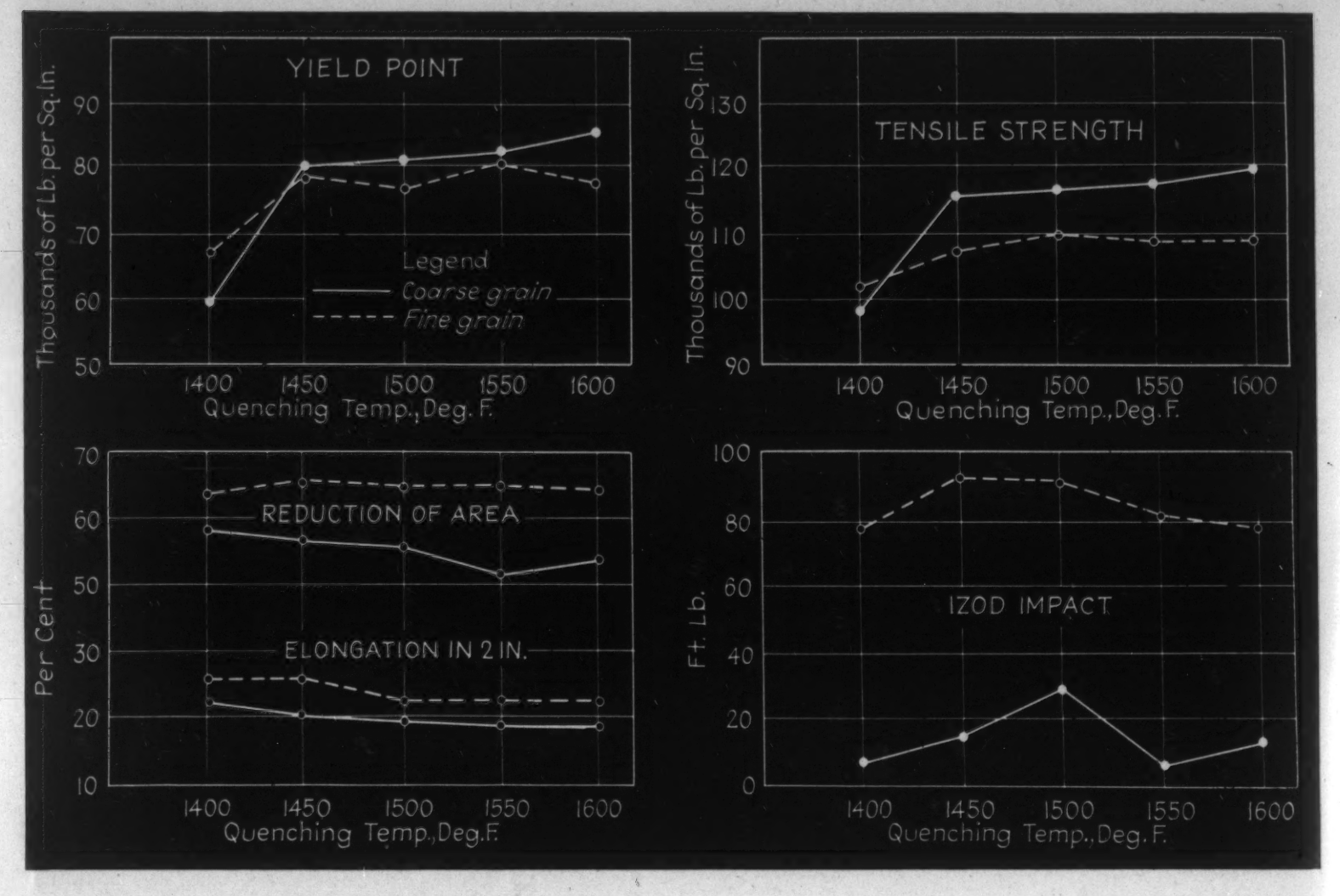
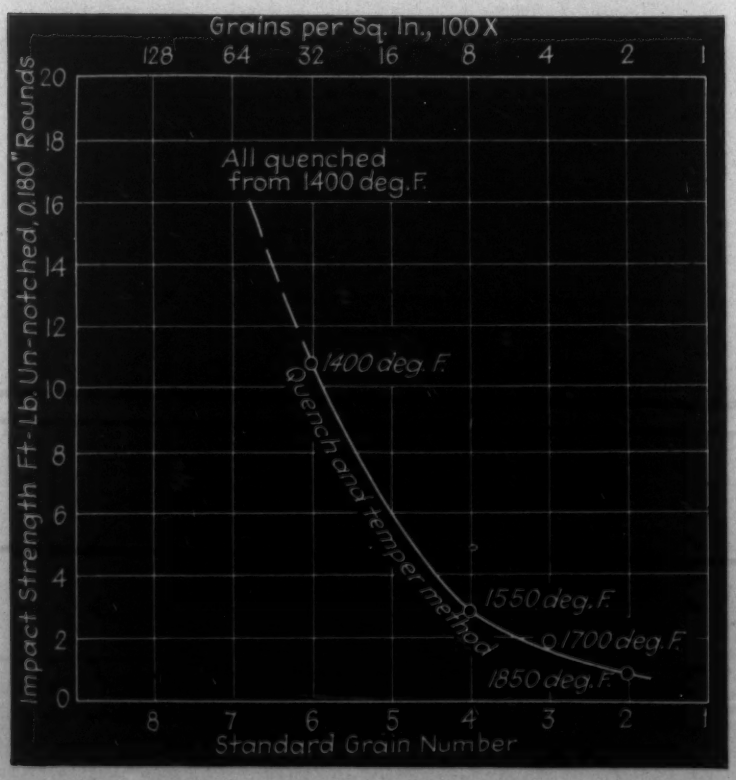


Fig. 21. The Relationship between the Impact Resistance of a Tempered Steel and its Previous Austenitic Grain Size. Note the increase in impact resistance for the finer-grained specimens. (Courtesy of E. S. Davenport).



sult from large dimensional changes that increase with increasing austenitic grain size. Coarse austenitic grained steels have higher internal stresses after quenching and are therefore more susceptible to grinding cracks than finer grained steels. Furthermore, more untransformed austenite is retained by the coarser grained steels. Due to their more rapid rates of transformation, finer grained steels are more susceptible to soft spots after quenching. Austenitic grain size also influences the tempering temperature for optimum hardness and toughness [57].

Daniloff, Mehl, and Herty [71] have shown that fine grained steels undergo little strain aging relative to that of coarse grained steels. Although the impact values for fine grained steels were slightly greater than those for coarse grained steels, after quench aging the fine grained steels exhibited greater decrease in impact resistance during aging. It is believed, however, that these relationships are not direct results of the austenitic grain size, but are due to the low quantity of oxygen in the highly deoxidized aluminum-killed steels.

The effect of austenitic grain size on several physical properties of a hypo-eutectoid steel is plotted in Fig. 22.

(To be concluded)

All references published in March issue.

Anodic Coating of Aluminum—Behavior of Alloy Constituents

by F. KELLER, G. W. WILCOX, M. TOSTERUD AND C. J. SLUNDER

Aluminum Research Laboratories, New Kensington, Pa.

In our issue for June we published an article entitled—"Anodically Oxidized Aluminum Alloys—Metallographic Examination"—by F. Keller and G. W. Wilcox of the Aluminum Research Laboratories.

This article supplements the first one, which pointed out a number of useful methods of examining such coatings. This one discusses the effects of alloying constituents. It is evident, say the authors, that from the results reported the different constituents have different oxidation characteristics which determine to some degree the results obtained when the various types of aluminum alloys are treated by the anodic oxidation process. "The anodic oxidation of aluminum and aluminum alloys has become a process of commercial importance and has led to many new uses for aluminum in recent years."—The Editors.

THE ANODIC OXIDATION OF ALUMINUM and aluminum alloys has become a process of commercial importance and has led to many new uses for aluminum during recent years. The anodic oxide coating imparts a variety of desirable properties to the metal such as improved resistance to abrasion and to corrosion and a pleasing appearance unobtainable with other protective or decorative films.

The principal electrolytes employed for the production of anodic coatings on aluminum contain sulphuric acid; some use is made also of electrolytes containing chromic acid. The main reaction in the anodic formation of oxide coatings is the same, regardless of the electrolyte used. Fundamentally, the coating is aluminum oxide with minor amounts of substances adsorbed from the electrolyte.

When commercial aluminum sheet is anodically oxidized in the electrolytes mentioned, the oxidation of the surface proceeds uniformly. The interface of metal and oxide remains almost as smooth as the original metallic surface and the thickness of the oxide layer is approximately proportional to the amount of current applied except when conditions are such that some of the oxide may be dissolved by the electrolyte. The characteristic appearance, under the microscope, of cross sections of oxide coatings formed on high purity aluminum sheet (99.95%) in electrolytes containing 15 per cent sulphuric acid and 9.5 per cent chromic acid respectively is illustrated by Figs. 1 and 2.

In the case of aluminum alloys which are to be anodically oxidized, the behavior of the alloying constituents becomes a matter of importance. When various elements are added to aluminum to form aluminum alloys, they may combine with the aluminum and form either solid solutions or aluminum-rich compounds which may be either soluble in the solid state or relatively insoluble. The phases that result from alloying generally are present in the form of micro-constituents.

In a general way, it has long been known that the presence of alloying constituents has an important influence on the electrolytic oxidation characteristics of an aluminum alloy. Some results of the effect of electrolytic oxidation on constituents have been published by Fischer[1], Brenner and Vogel[2], and Röhrig and Käpernick[3]. Their work showed the effects of the treatment on a few constituents only. It is evident, however, that it is desirable to have a fundamental knowledge of the behavior of the different constituents as they are affected by the oxidation process.

The metallographic characteristics of the constituents common to commercial aluminum alloys have been described by Dix and Keith[4] and by Keller and Wilcox.[5] These constituents form the basis of this investigation. The electrolytic oxidation characteristics of the constituents were determined on a special group of samples made from high purity aluminum (99.95% Al) and high purity alloying metals. The amounts of the alloying metals added in making these samples were, in most cases, greater than those usually found in commercial alloys. This was done in order to obtain large constituent particles to facilitate the study of their anodic oxidation characteristics.

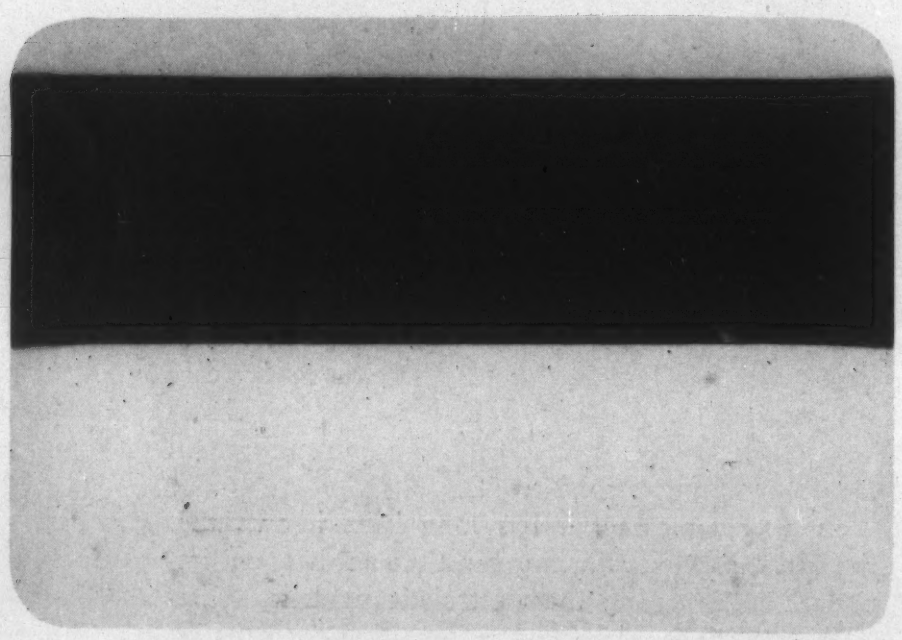
The samples were in the form of 2 x 3 x 3/8-in. slugs which were cast in a hot graphite mold and slowly cooled to obtain large particles of constituent. These cast samples were prepared for electrolytic oxidation by machining one cast face and by smoothing the machined face on fine metallographic emery paper. A description of the samples prepared for this investigation is included in the Table.

TABLE OF COMPOSITION OF SAMPLES PREPARED FOR INVESTIGATION OF THE CHARACTERISTICS OF ALUMINUM CONSTITUENTS

Alloy No	Constituent[a]	Nominal Composition
1	Si	20% Si
2	$CrAl_7$	5% Cr
3	Al-Cr-Fe	4% Fe, 4% Cr
4	$CuAl_2$	10% Cu
5	βAl-Mg	15% Mg
6	Al-Cu-Mg	6% Mg, 4% Cu
7	Al-Cu-Ni	4% Cu, 4% Ni
8	$MgZn_2$	5% Mg, 25% Zn
9	$NiAl_3$	7% Ni
10	$FeAl_3$	6% Fe
11	Al-Mn	5% Mn
12	Mg_2Si	25% Mg_2Si
13	αAl-Cu-Fe	2% Fe, 2% Cu
14	βAl-Cu-Fe	2% Fe, 5% Cu
15	αAl-Fe-Si	3% Fe, 9% Si
16	βAl-Fe-Si	5% Fe, 15% Si
17	Al-Fe-Mn	26% Fe, 3% Mn
18	Al-Cu-Fe-Mn	2% Fe, 2% Cu, 2% Mn

[a] Constituents known to be intermetallic compounds are identified by chemical formulae. Where the exact composition is not known the constituents are designated by abbreviations of the chemical elements, as for example, Al-Fe-Mn.

Fig. 1. This shows the typical appearance of a cross section through a sample of 99.95% aluminum sheet which had been oxidized in a sulphuric acid electrolyte for 2 hrs. The dark band at the top is the oxide coating on one surface of the sheet. Reflected light, vertical illumination. Unetched. 500X.



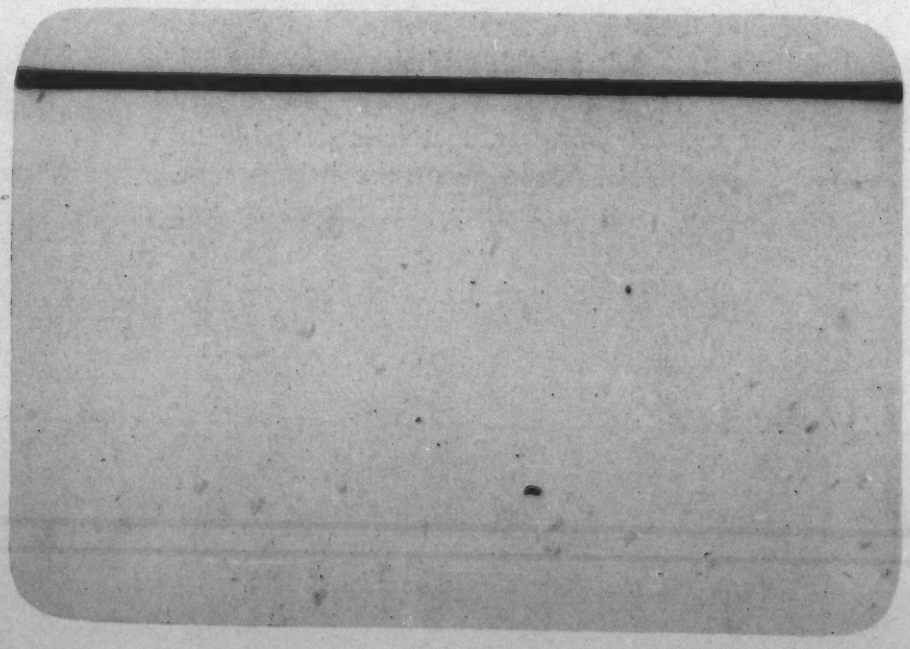


Fig. 2. This shows the typical appearance of the oxide coating on a sample of the same material which had been oxidized in a chromic acid electrolyte for 1 hr. Reflected light, vertical illumination. Unetched. 500X.

The cast samples with the various micro-constituents were electrolytically oxidized in electrolytes containing 15 per cent sulphuric acid and 9.5 per cent chromic acid respectively and were sectioned and polished by the metallographic methods described by Keller and Wilcox.[5]

Classification of Constituents

Microscopic examinations of the cross sections of the different oxidized samples listed in the Table revealed that the various constituents in aluminum alloys could be grouped under three classifications. These are: (1) alloying constituents in solid solution, (2) constituents not appreciably dissolved or oxidized by the anodic oxidation treatment, and (3) constituents which are readily dissolved or oxidized by the treatment.

Alloying Constituents in Solid Solution

The alloying constituents which form solid solutions with aluminum are principally copper, magnesium, silicon and zinc. When these constituents are uniformly dispersed in solid solution in the aluminum, the uniformity of the oxide coating is similar to that obtained in the case of the pure metal.

Constituents Not Appreciably Dissolved or Oxidized by the Oxidation Treatment

Of the 18 constituents listed in the Table, five, (Si, Al-Mn, $CrAl_7$, Al-Cr-Fe and Al-Cu-Fe-Mn) were not dissolved or oxidized as rapidly as the aluminum matrix by anodic treatment in a sulphuric acid electrolyte, and four, (Si, Al-Mn, Al-Cr-Fe and Al-Cu-Fe-Mn) were not dissolved or oxidized as rapidly as the aluminum matrix in a chromic acid electrolyte. It is to be expected, therefore, that these constituents would remain in the anodic coating in

Fig. 3. Alloy No. 1—Si

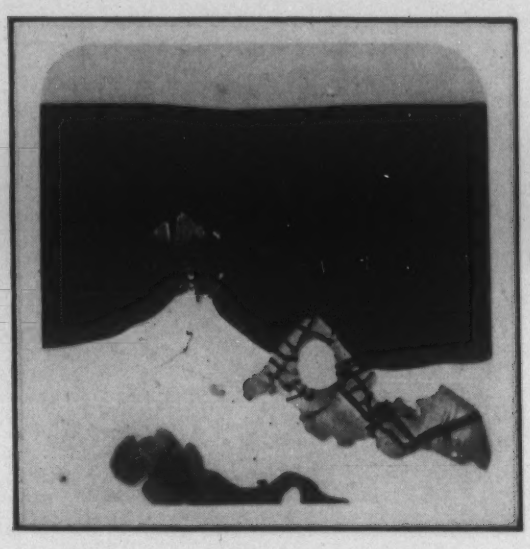


Fig. 4. Alloy No. 2—$CrAl_7$

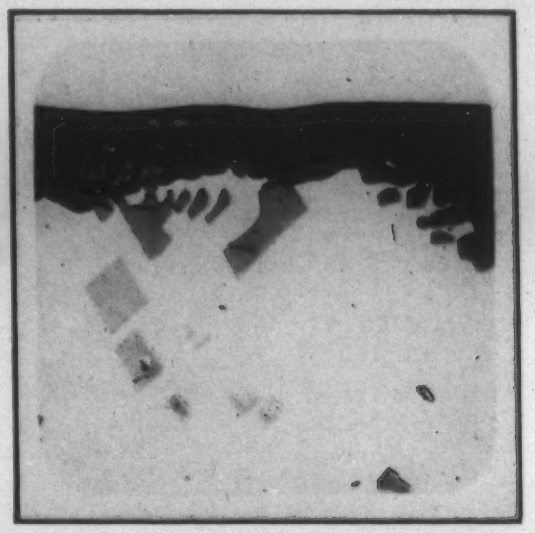


Fig. 5. Alloy No. 3—Al-Cr-Fe

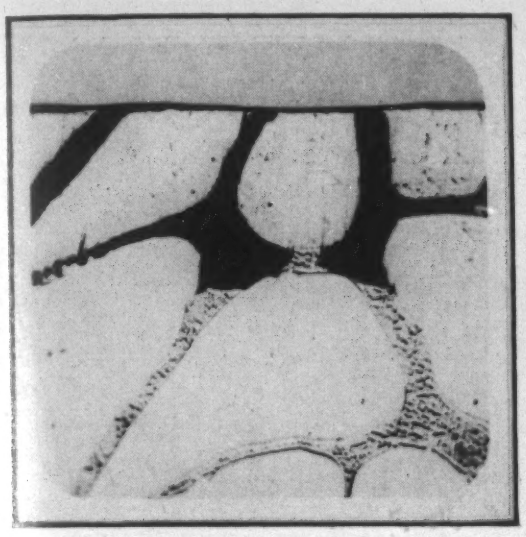


Fig. 6. Alloy No. 4—$CuAl_2$

Fig. 7. Alloy No. 5—βAl-Mg

Fig. 8. Alloy No. 6—Al-Cu-Mg

Fig. 9. Alloy No. 7—Al-Cu-Ni

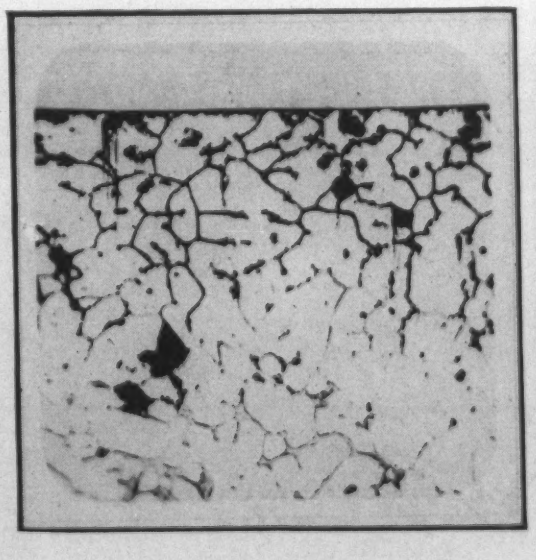


Fig. 10. Alloy No. 8—$MgZn_2$

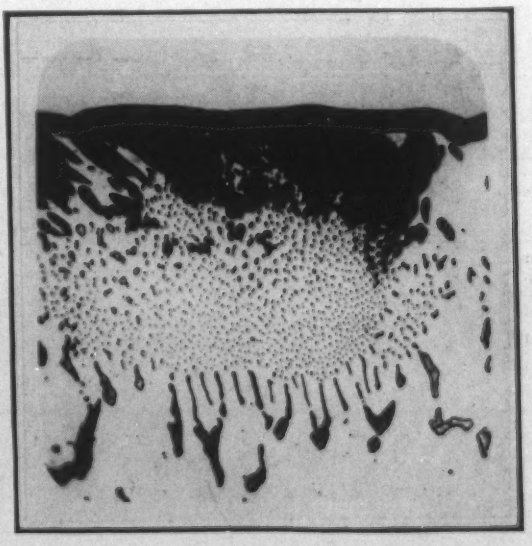


Fig. 11. Alloy No. 9—$NiAl_3$

OXIDATION CHARACTERISTICS OF CONSTITUENTS IN ELECTROLYTE CONTAINING SULPHURIC ACID. All illustrations are at a magnification of 250X except Fig. 10; it is at 100X.

a substantially unchanged condition. All the other constituents were dissolved or oxidized either at the same rate or more rapidly than the aluminum matrix. Under some conditions, however, it has been observed that constituents such as $FeAl_3$ and Mg_2Si, which should be dissolved or oxidized during the anodic treatment, are present in the oxide coating. Apparently, these constituents were cut off from the matrix before they had been completely dissolved or oxidized by the electrochemical process. As long as the constituents make electrical contact with the matrix, the electrochemical action will continue and the results will depend upon the electrolytic potential of the constituent in relation to the potential of the matrix.

Silicon furnishes the best example of a constituent

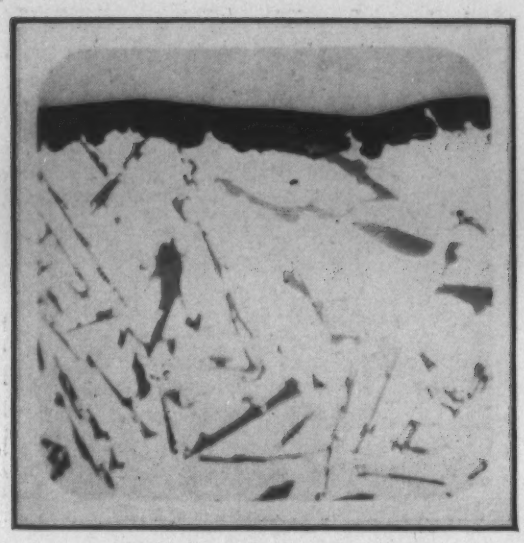


Fig. 21. Alloy No. 1—Si

Fig. 22. Alloy No. 2—$CrAl_7$

Fig. 23. Alloy No. 3—Al-Cr-Fe

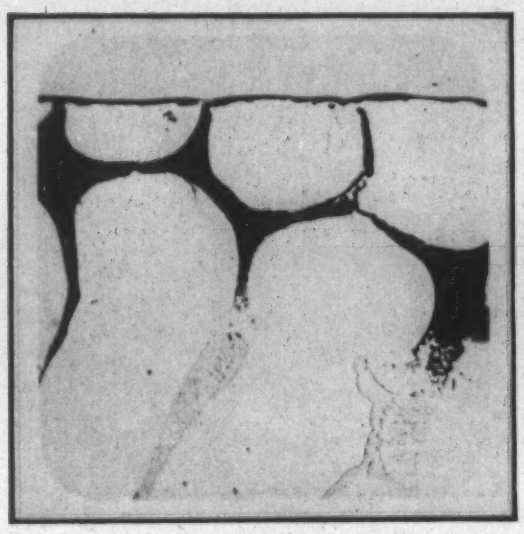


Fig. 24. Alloy No. 4—$CuAl_2$

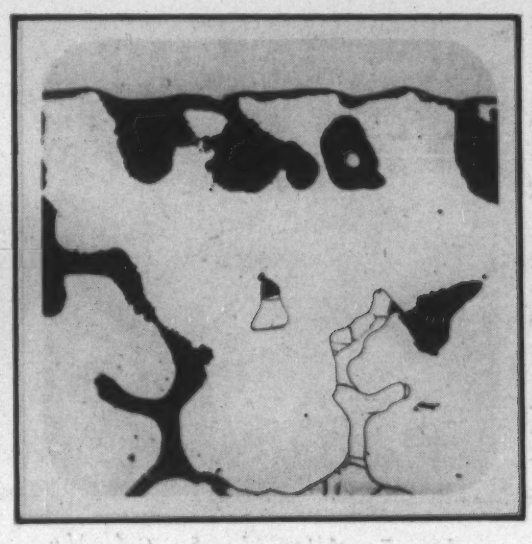


Fig. 25. Alloy No. 5—βAl-Mg

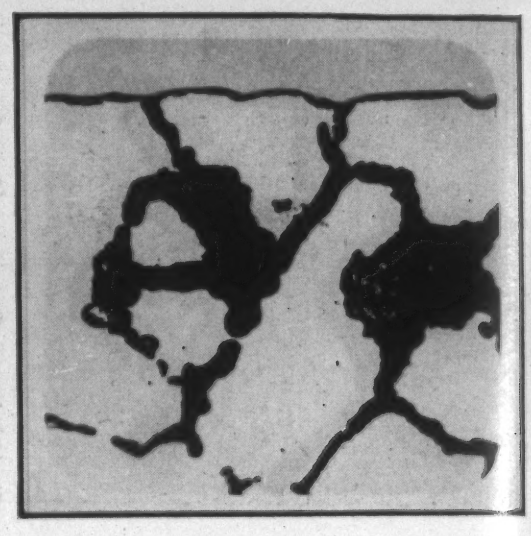


Fig. 26. Alloy No. 6—Al-Cu-Mg

Fig. 27. Alloy No. 7—Al-Cu-Ni

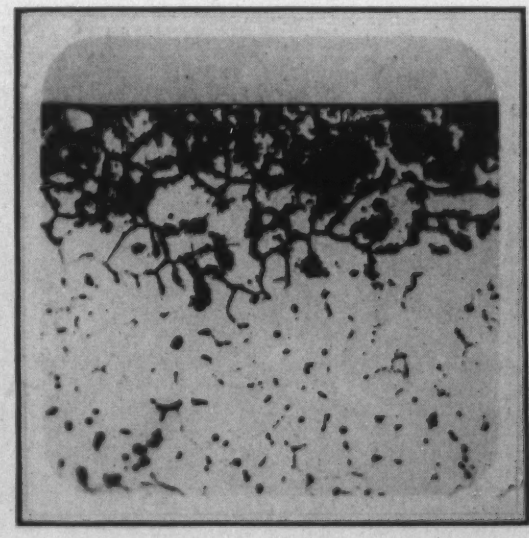


Fig. 28. Alloy No. 8—$MgZn_2$

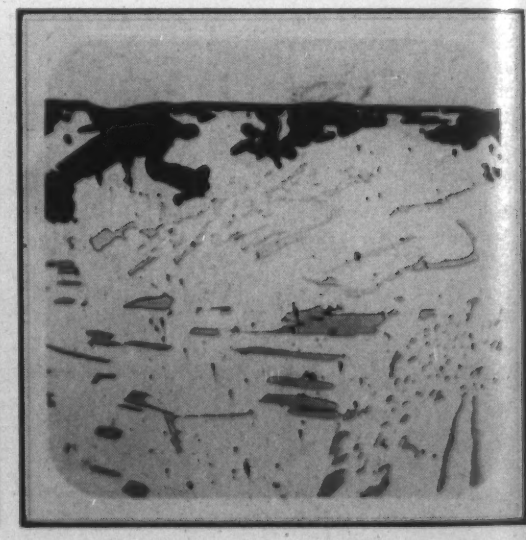


Fig. 29. Alloy No. 9—$NiAl_3$

OXIDATION CHARACTERISTICS OF CONSTITUENTS IN ELECTROLYTE CONTAINING CHROMIC ACID. All illustrations are at a magnification of 250X except Fig. 28; it is at 100X.

which is not noticeably dissolved or oxidized by the anodic treatment. When elemental silicon is present in excess of its solid solubility in an aluminum alloy or as a precipitate resulting from thermal treatment, followed by slow cooling or a low temperature aging treatment, it is not dissolved or oxidized during the anodic treatment. Examples of this are shown in Figs. 3 and 21. In these micrographs, particles of silicon may be seen in the anodic coating on the samples. These particles occupy the same relative position in the oxide coating as they did in the metal from which the oxide was formed.

An explanation for the occurrence of elemental silicon in the anodic coating is as follows: When

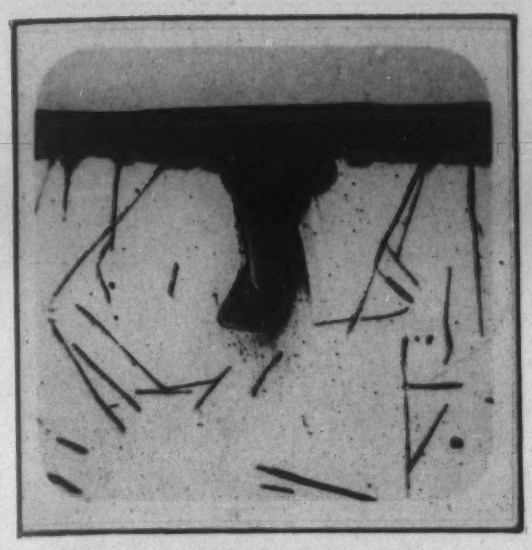


Fig. 12. Alloy No. 10—$FeAl_3$

Fig. 13. Alloy No. 11—Al-Mn

Fig. 14. Alloy No. 12—Mg_2Si

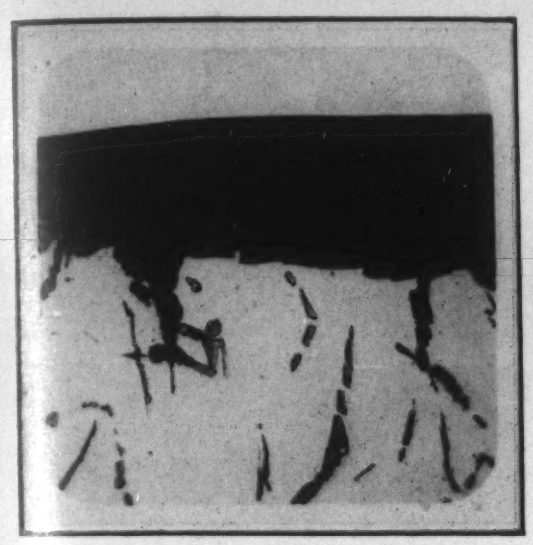


Fig. 15. Alloy No. 13—αAl-Cu-Fe

Fig. 16. Alloy No. 14—βAl-Cu-Fe

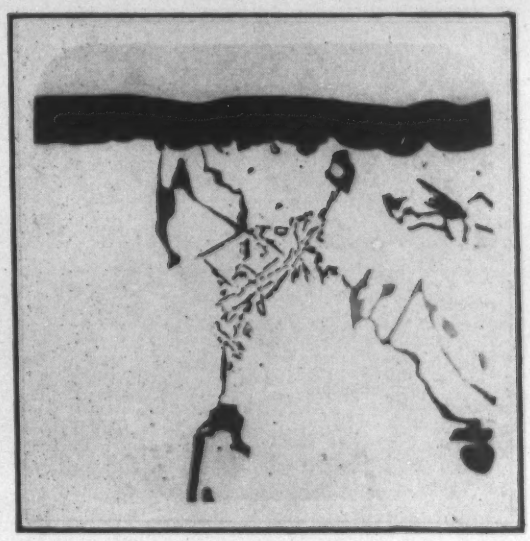


Fig. 17. Alloy No. 15—αAl-Fe-Si

Fig. 18. Alloy No. 16—βAl-Fe-Si

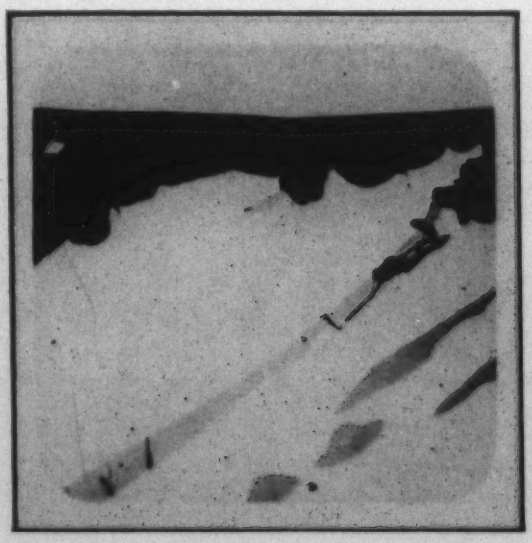


Fig. 19. Alloy No. 17—Al-Fe-Mn

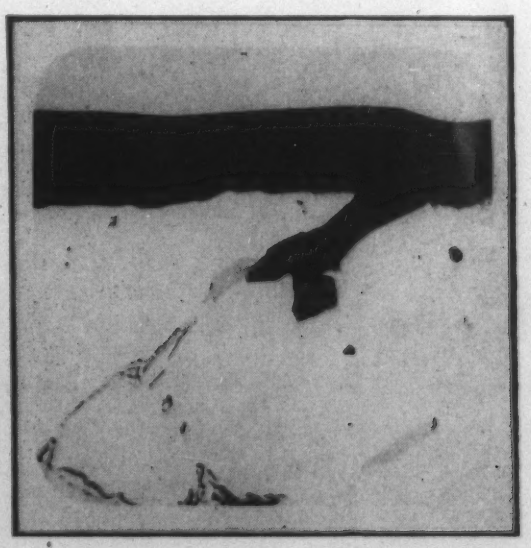


Fig. 20. Alloy No. 18—Al-Cu-Fe-Mn

OXIDATION CHARACTERISTICS OF CONSTITUENTS IN ELECTROLYTE CONTAINING SULPHURIC ACID. All illustrations are at a magnification of 250X.

a piece of elemental silicon is made anode in a sulphuric acid electrolyte, the normal current density of 12 amperes per sq. ft. is not obtained until a potential of about 64 volts is applied as against a potential of about 15 volts required for aluminum. It is obvious, therefore, that in an aluminum-silicon alloy the current will pass to the aluminum matrix, because it is the low resistance path, and around the silicon particles without altering the silicon. In some cases, small particles of aluminum may be blocked by the silicon particles from receiving any current; thus, they remain in the oxide coating as unoxidized particles of aluminum. Moreover, the absence of a metallic luster and the development of a brown to

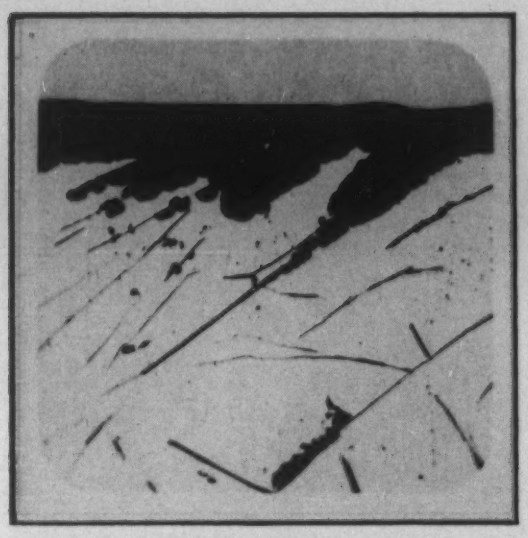


Fig. 30. Alloy No. 10—$FeAl_3$

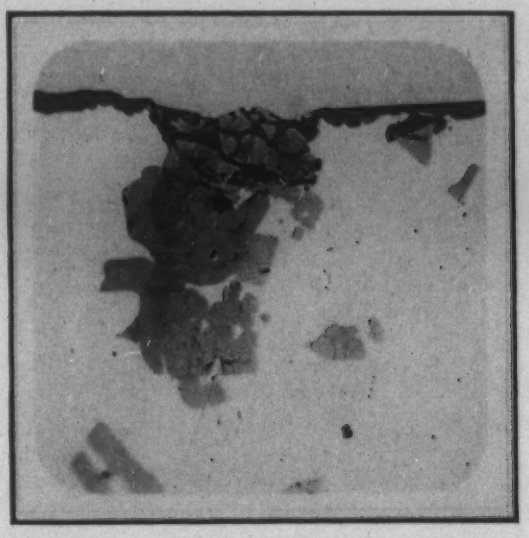


Fig. 31. Alloy No. 11—Al-Mn

Fig. 32. Alloy No. 12—Mg_2Si

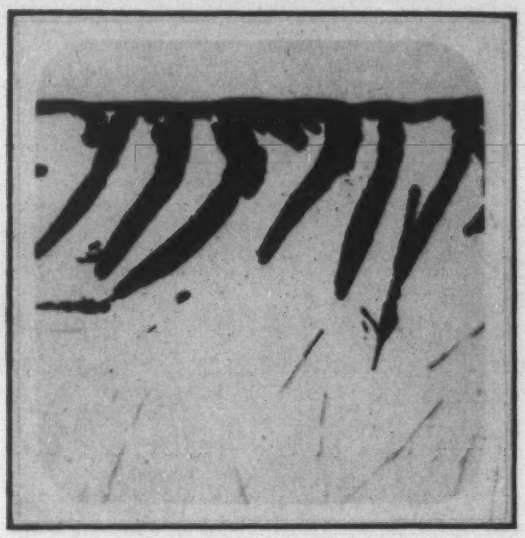


Fig. 33. Alloy No. 13—αAl-Cu-Fe

Fig. 34. Alloy No. 14—βAl-Cu-Fe

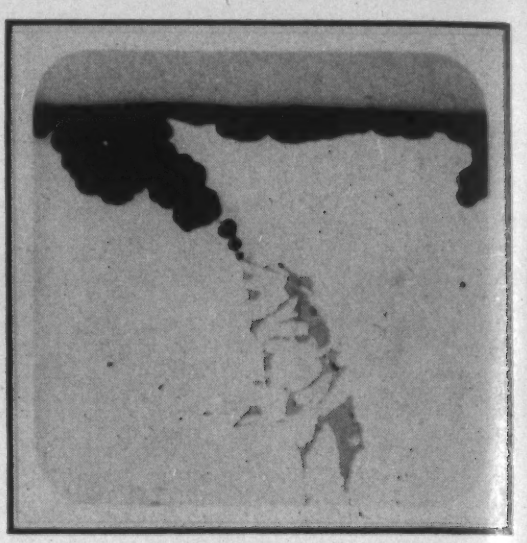


Fig. 35. Alloy No. 15—αAl-Fe-Si

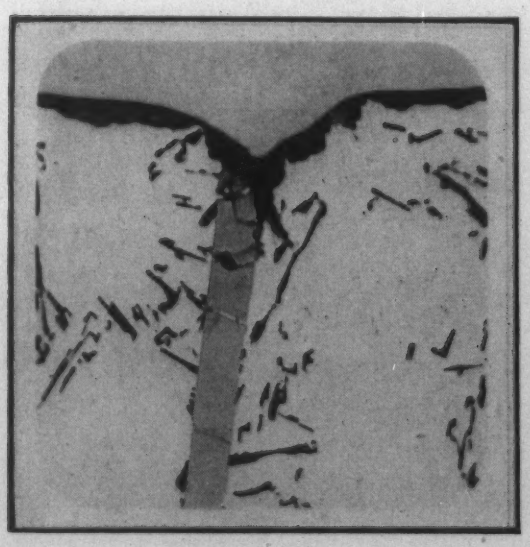


Fig. 36.—Alloy No. 16—βAl-Fe-Si

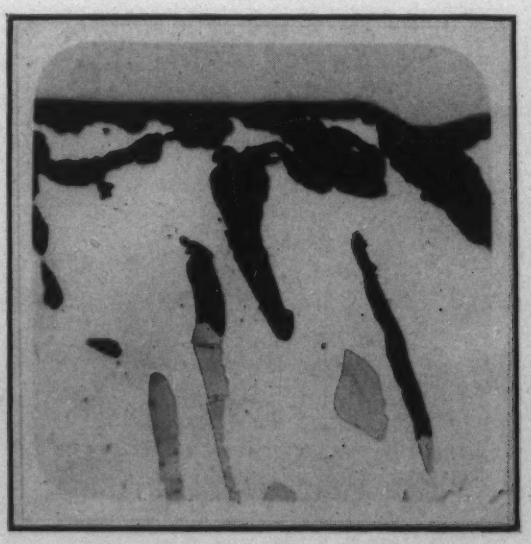


Fig. 37. Alloy No. 17—Al-Fe-Mn

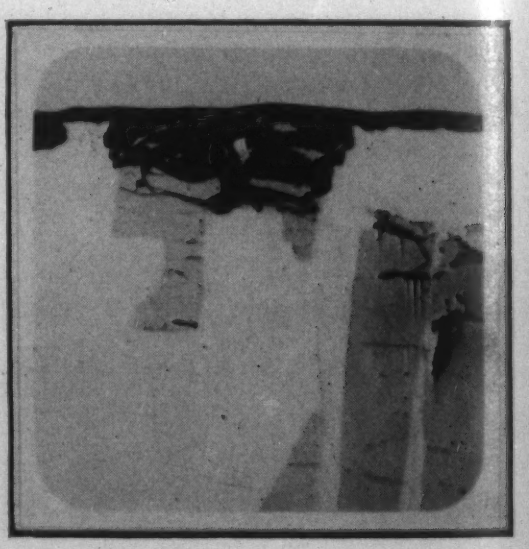


Fig. 38. Alloy No. 18—Al-Cu-Fe-Mn

OXIDATION CHARACTERISTICS OF CONSTITUENTS IN ELECTROLYTE CONTAINING CHROMIC ACID. All illustrations are at a magnification of 250X.

black color under some circumstances in aluminum-silicon alloys are readily explainable by the irregular interface and the variable light reflections from the small and large particles of elemental silicon which are dispersed throughout the anodic coating.

If the amount of silicon in the alloy is such that it can be dissolved completely by thermal treatment, the characteristics of the anodic coating are much the same as those obtained on pure aluminum. The oxide coating is relatively transparent and the metal oxide interface is smooth. An analysis of such an oxide coating reveals that the coating contains silica (SiO_2) instead of elemental silicon. Furthermore, upon stripping with sulphuric acid, it will be ob-

served that as the alumina is dissolved, the coating is held together by a gelatinous film of silicic acid which peels from the coating readily when a stream of water is directed against it. A similar stripping test applied to any alloy which contains elemental silicon, shows the presence of a silicic acid film which forms from the silicon in solid solution, of granular black crystals of elemental silicon which sink to the bottom of the stripping solution and of a small amount of very finely divided particles of elemental silicon which have a yellow to brown color and which float on the surface of the solution. The fine and coarse particles are elemental silicon of different degrees of aggregation which have been left substantially unaltered by the anodic oxidation treatment.

Constituents Dissolved or Oxidized by the Anodic Treatments

With the exception of the constituents just described it was apparent from the examination of the cast samples that the other constituents found in commercial aluminum alloys and listed in the Table are dissolved or oxidized either to the same extent or more readily by the current than the aluminum matrix during the oxidation treatment. A typical example of a constituent which is rapidly dissolved or oxidized is illustrated in Fig. 6. This is the intermetallic compound $CuAl_2$. On the 10 per cent aluminum-copper alloy cast sample, only a very thin film of aluminum oxide was formed when the sample was oxidized in a sulphuric acid electrolyte for 2 hrs. at a current density of 12 amperes per sq. ft. Similar oxidation characteristics are observed with the βAl-Mg, $MgZn_2$, Al-Cu-Mg, αAl-Cu-Fe, βAl-Cu-Fe, and Al-Cu-Ni constituents.

In alloys containing these constituents, the oxidation apparently follows the constituent particles along the grain boundaries and the dendrite arms and penetrates the metal to an appreciable depth. Thus, the aluminum surface area available to conduct current is greatly increased and results in a decrease in current density as calculated from the original flat surface. Furthermore, the constituent network takes a large part of the current; thus, only a thin oxide coating is formed on the matrix.

A study of the effects of oxidation in chromic acid electrolyte on the various constituents will disclose that many of the constituents are dissolved or oxidized more readily and to a greater degree than when sulphuric acid electrolyte is employed. Some constituents which are not oxidized in the sulphuric acid electrolyte are oxidized readily in the chromic acid electrolyte. This condition is to be expected, however, since a much higher potential is required to produce an anodic coating on aluminum when the chromic acid electrolyte is used.

General Oxidation Characteristics of Constituents

The oxidation characteristics of the micro-constituents commonly found in aluminum alloys are illustrated in Figs. 3 to 20 inclusive for the samples which were oxidized in sulphuric acid electrolyte and by Figs. 21 to 38 inclusive for the samples oxidized in chromic acid electrolyte. All micrographs shown in Figs. 3 to 38 inclusive are at a magnification of 250X except those in Figs. 10 and 28; they are at a magnification of 100X.

The general character of the oxide coatings on these samples indicates the manner in which the various alloys are affected by the anodic treatment. It is believed that, under some conditions and with some constituents, the constituent may be largely dissolved during the oxidation process and converted to colored substances which remain in the oxide coating. It is known that under some circumstances the manganese in an aluminum-manganese alloy may be oxidized to manganese dioxide in the oxide coating and imparts a dark brown color to the oxide coating.

Conclusions

The fundamental facts regarding the oxidation characteristics of various micro-constituents of aluminum alloys revealed by this investigation may be employed to explain variations in results obtained in the anodic oxidation of commercial aluminum alloys. It is evident from the results reported in this paper that the different constituents have different oxidation characteristics and that these characteristics determine to some degree the results obtained when the various types of aluminum alloys are treated by the anodic oxidation process.

Acknowledgment

The authors wish to acknowledge the many helpful suggestions from J. D. Edwards, E. H. Dix, Jr. and R. B. Derr, under whose supervision this work was done.

References

[1] H. Fischer, "Progress in the Field of Electrolytic Surface Treatment of Light Metals," *Zeitschrift für Metallkunde*, Vol. 29, p. 319, 1937.

[2] P. Brenner and H. U. v.Vogel, "Influence of Structure on the Color of Eloxal Coatings on Al-Mg Alloys," *Aluminum*, Vol. 19, No. 10, pp. 696-698, November, 1937.

[3] H. Röhrig and E. Käpernick, "Regarding the Behavior of the Precipitated Structural Constituents in the Electrolytic Oxidation of Aluminum Alloys and Regarding Their Influence on Some Properties of the Oxide Coatings," *Metallwirtschaft*, Vol. 17, No. 24, pp. 665-668, June 17, 1938.

[4] E. H. Dix, Jr., and W. D. Keith, "The Etching Characteristics of Constituents in Commercial Aluminum Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 317, (1926)

[5] F. Keller, Jr., and G. W. Wilcox, "Polishing and Etching of Constituents of Aluminum Alloys," *Metal Progress*, Vol. 23, April, 1933, p. 45.

EDITORIALS (*Continued from page 197*)

have become available and periodical publication goes on apace. By these, better education and continued self-education may be had. The need for interpretation and for facilitating the application of practice of the increasing mass of scientific information is, today, even more pressing than it was 10 years ago.

The expansion of scientific metallurgy, in spite of the decade's handicaps, is truly remarkable. If we could only drown a few selected politicians and dictators as we do kittens that won't become housebroken, the technicians of the world could proceed unhampered to make better and cheaper goods for human consumption. The technician makes use of the physical laws of the universe, the politician tries to warp equally stringent but less well understood economic laws to suit his temporary purpose. Ultimately, those laws will defeat the politicians and the political clouds of the past decade will be swept away. Economies and improvements due to the metallurgical engineers' sane utilization of fundamental principles will be a major factor in cleaning up the mess we find ourselves in today.

We have faith in the type of men who are dealing with the theory and practice of metallurgy. They, and the technicians in other fields, who improve and innovate, are our chief reliance for better times.—H. W. G.

Bugs

In a few paragraphs by C. W. Rice, in the G. E. *Review* for November, 1938, dealing with hydrogen cooled electric generators and the like, he comments that Dr. Whitney thought, in 1921, that hydrogen cooling should be a good idea, but before the idea could be put to use, a seal had to be devised to hold the hydrogen. Rice goes on to say "*during the next few years* this obstacle was surmounted," (Italics ours) that in 1928 it was possible to apply the scheme to synchronous condensers, in 1937 to superposed turbine generators, and that "it is probably safe to say that the future will see practically all large turbine generators operating in hydrogen."

Rice uses the italicized phrase as a matter of course. All people who expect quick magic from research, without patient struggle in elimination of "bugs," might well connect this nonchalant attitude with G. E. success in development.—H. W. G.

The Foundry Industry

We recall quite vividly that some years ago there were predictions, often from sources from which they were least expected, that the foundry industry was on its last legs, particularly in respect to gray iron. There were some, however, who scoffed at such sentiments. In recent years we have seen such predictions rendered ridiculous.

The latest demonstration of the vitality and progressiveness of the foundry industry, technically at least, was the annual convention in May, of the American Foundrymen's Association at Cincinnati. In that city there were over 1300 registered delegates and visitors—the largest attendance on record at a gathering not featured by an exhibition of equipment. They represented an industry "employing in the United States about 360,000 men with an annual production of 10,000,000 tons of ferrous and non-ferrous castings worth approximately $1,000,000,000," according to President Post. "Some of the foundries employ 3000 to 5000 men, especially those in connection with the automobile, agricultural equipment, railroad and other industries."

Attendance at the many technical sessions was large and the interest was keen. And rightly so, because the metallurgical and metallurgical engineering problems which have developed with the introduction of alloys in gray iron, steel, malleable and so on, with the heat treatment of such products, with the use of controlled atmospheres, with the development of new methods of melting, with the short cycle annealing of malleable iron, and so on, demand skilled technical consideration and guidance.

We were impressed with the serious zeal of these foundrymen from all walks of the industry and were convinced that the future of progress in the foundry industry was never brighter.—E. F. C.

Magnesium

Two facts in particular have recently come to our attention which emphasize the growing industrial importance of the metal magnesium.

According to statistics from the U. S. Bureau of Mines, "the production (sales) of primary magnesium" in this country in 1938 was greater than ever before. The 4,819,617 pounds exceeded by about 6 per cent the 1937 total. It was over five times the total in 1929. These totals include metal exported. Actual data on exports are not available, but it is indicated that the shipments to Japan and Europe were unusually large. While American consumption was less last year than in 1937, due to economic conditions, the larger exports account for the increased production.

From Washington and through consular channels, the statement is published that Germany's estimated output of magnesium in 1938 amounted to between 12,000 and 13,000 metric tons against about 10,000 tons in 1937. In our news items in the May issue, (page MA 314) attention was called to the use of non-ferrous metals in American and foreign automobiles. In this the extensive use of magnesium by Germany was featured.

The expanding consumption in Germany is due largely to the program of replacing imported materials where possible. The engineering value of this metal, properly alloyed and heat treated, is becoming more widely recognized. Without doubt the consumption of magnesium alloy castings and other structural products in the aircraft industry established a new peak last year in this and other countries. In this progress the research work of the metallurgical engineer stands out.—E. F. C.